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AND

PROCEEDINGS OF THE SOCIETY OF ARTS.

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PROCEEDINGS OF THE SOCIETY OF ARTS.

THIRTY-NINTH YEAR, 1900–1901.

BOSTON, April 11, 1901.

THE 552d regular meeting of the SOCIETY OF ARTS was held on this day at 8 P.M. at the Rogers Building, President Pritchett presiding. Fifty persons were present.

The following candidates were elected to Associate Membership: Messrs. John S. Eynon, C. E. Sherman, and Joseph C. Riley.

Dr. George W. Field, Biologist to the Rhode Island Agricultural Experiment Station and Lecturer on Economic Zoölogy at the Institute, spoke on "The Increase of the Food Supply of Mankind through the Cultivation of Marine Animals: a Problem in Economic Zoölogy."

"The shore and deep sea fisheries were the economic foundation of human existence in New England. The numerous shell heaps along the coast testify to the importance of the shellfish to the Indians; the chronicles of that first winter on Plymouth shores tell how the Pilgrims 'sucked the abundance of the sea.' The settlers of Boston and the North Shore laid the foundations of prosperity in salt codfish for export trade.

"Massachusetts is well-nigh alone in her fortunate aquatic geographical situation, being at the meeting line of the cold northern

waters remarkable for the small number of species but enormous numbers of individuals, *e. g.*, cod, herring, lobster, oyster, clams, scallops, etc., and the warm tropical waters remarkable for the untold multitude of different species but with a relatively small number of individuals of each species.

"The physiographic features of Massachusetts likewise made for great productiveness; the indented coast, with shallow bays, and numerous rivers cause a rapid growth of marine vegetation, which becomes the pasture for enormous quantities of marine animals, which, in turn, become food for man. This change of inorganic substance washed from the land into plant and animal substance is rapid on our shores, and the productive capacity of any area is dependent upon the rate of change, just as a business enterprise may prosper according to the rapidity with which the capital is turned over.

"Aquatic plant and animal life falls into two groups: the stationary, fixed to the bottom, and the freely wandering, the Plankton. The Plankton is the more valuable for producing crops of food animals, and a study of the Plankton permits a forecast of the prospective and actual economic value of any given area of water.

"Water under favorable conditions produces a greater quantity of nitrogenous food material than an equal area of land. Water is as amenable to cultivation as land, and conditions are practically duplicated. The same conditions which have led to the necessity of cultivating the land are beginning to call urgently for the cultivation of the water. Increasing population results in increased demand, soon exceeding the supply. Unless the supply be augmented, we draw on nature's capital, and biological bankruptcy is sure to follow. The destruction of adult animals by man results in upsetting nature's equilibrium, and upon man comes the responsibility for making the proper adjustments. Civilization continuously restricts the areas available for marine animals. Human cupidity and lack of foresight lead to improper laws. 'That the products of the sea belong to the people as a common heritage guaranteed by the constitution' is narrowly interpreted in the interest of those who catch or sell the products, and against the interests of 'all the people' who are dependent upon the products of both land and sea for reducing the cost of living. The public, through the machinery of the state, has decided upon its relations to the ownership of lands and their products; similar decisions must be made in regard to water areas. This

is especially important for the clam industry of New England. Uniformity in biological legislation for sections which have the same biological conditions is feasible and necessary. Steps should be taken to make uniform laws in New England in regard to the lobster, clam, oyster, scallop, game, fish, birds, injurious insects, and infectious plant diseases.

"Public biological museums should be located in every city, especially conducted for giving reliable information upon all economic questions in regard to plants and animals. Each collection should at first deal only with the species and conditions found in that immediate vicinity. In this way a reasonable degree of completeness might soon be obtained.

"The problems immediately connected with the supply of lobsters are numerous, important, and difficult of solution. The aggressiveness of the lobster, young and adult, precludes sociability, and therefore the number which can live in a given area is strictly limited. The natural breeding ground, too, of the species is comparatively restricted; it is bounded on the north by the icy waters of the Strait of Belle Isle, between Newfoundland and Labrador, while the most southern point where stragglers have been taken is the coast of North Carolina, an area approximately 1,300 miles long and thirty to fifty miles wide, or about 50,000 square miles. The coast of New England should produce the greatest number of marketable lobsters, since it is at about the middle of the range.

"In spite of assertions to the contrary, it would seem that the following figures, compiled from the returns to the Massachusetts Commissioners of Inland Fisheries and Game, indicate conclusively that there has been a steady and rapid decrease in the lobster supply. Of the nine years for which returns of Massachusetts are available for study, three show an increase in the number of lobsters caught; but, unfortunately, this is the result of a larger increase in the number of men and traps employed, while the other six years show a decrease in all points.

"The figures are from 1893 to 1900, inclusive:

	Number of men employed.	Number of traps.	Adult lobsters.	Egg-bearing lobsters reported.
Total increase in 1894, 1896, 1900, over the preceding year.	110	8,027	40,867	2,156
Total decrease in other six years.	193	11,053	544,100	19,259
Net decrease in last nine years.	83	3,026	504,233	17,103

Or net decrease given in percentages:

In number of men employed,	21.2%
In number of traps used,	17.7%
In number of large lobsters taken,	43.9%
In number of egg-bearing lobsters reported,	52.2%

"This shows that there is a smaller net decrease in the number of men; that these men are compelled to use a greater number of traps per man on the average, and that the number of lobsters above 10½ inches has decreased very markedly (by nearly one-half), while the number of egg-bearing lobsters reported has diminished more than one-half.

"The main cause of the decrease is the increased demand, leading to the destruction of the sexually mature adults; an increased demand which has not been met by a corresponding increase in the supply. The demand has been stimulated by the gastronomic devices, but the source of supply has received little popular attention beyond the short-sighted policy of catching as many lobsters as possible.

"Ultimately man must assume the same relations to the lobster and fishing industries as has come about with domesticated animals and plants. Thus far no satisfactory method has been devised for domesticating and propagating the lobster; the necessity for it is only beginning to be urgent. The method of life, the seasonal immigrations from deep to shallow water, the slow rate of development and growth, and, above all, the combativeness and cannibalism of the old and young, all unite to make the problem of artificial cultivation difficult to handle, though by no means hopeless in the present state of our knowledge. The great need is for study, correlation, and interpretation upon methods of rearing the young and of catching lobsters of the size best adapted for the market, with special reference to maintaining and increasing the supply."

The thanks of the Society were most heartily extended to Dr. Field for his able paper.

BOSTON, April 25, 1901.

The 553d regular meeting of the SOCIETY OF ARTS was held on this day at 8 P.M., Room 11, Rogers Building, Professor Peabody presiding. One hundred persons were present.

The report of previous meeting was approved. The Chairman appointed Mr. Leach, Dr. Walker, and Professors Peabody, Bartlett,

and Laws to serve on a committee to nominate the Executive Committee for the year 1901–1902. Messrs. William A. Hovey and W. O. Sawtelle were elected to Associate Membership.

Professor J. E. Denton, Stevens Institute of Technology, gave a very instructive address on "Principles of Action of Various Types of Refrigerating Machines."

BOSTON, May 16, 1901.

The 39th Annual Meeting (the 554th regular meeting) of the SOCIETY OF ARTS was held at the Institute on this day at 8 P.M., with President Pritchett in the chair. Fifty-six persons were present.

The records of the previous meeting were read and approved. The Secretary read the Annual Report of the Executive Committee. It was voted that the report be accepted and placed on file.

ANNUAL REPORT OF THE EXECUTIVE COMMITTEE.

The first meeting of the SOCIETY OF ARTS for the present year was held on October 11, 1900. Fourteen meetings have been held, the average attendance being 143. This shows a considerable gain over last year.

The following papers have been read:

"Color Photography," by Professor Louis Derr.

"Some Experiments in Architectural Acoustics," by Professor Wallace C. Sabine.

"America's Contribution to Our Knowledge of the Size and Figure of the Earth," by Dr. Henry S. Pritchett, President of the Institute of Technology.

"Applied Science in the Textile World," by Professor W. W. Crosby.

"Landscape Architecture in This Country," by Mr. Guy Lowell.

"Shipment of Freights to Europe," by Mr. William H. Lincoln.

"Photography with the Great Visual Telescope of the Yerkes Observatory," by Professor George E. Hale.

"The Designing of the Buffalo Exposition," by Mr. Robert S. Peabody.

"A Forest Policy for the United States," by Mr. Gifford Pinchot.

"The Use of the Microscope in the Study of the Chemical Constitution and Physical Properties of Metals," by Dr. Henry Fay.

"Electrical Wave-Transmission," by Professor M. I. Pupin.

"The Increase of the Food Supply of Mankind through the Cultivation of Marine Animals: a Problem in Economic Zoölogy," by Dr. George W. Field.

"Principles of Action of Various Types of Refrigerating Machines," by Professor J. E. Denton.

"Cotton from Seed to Bale," by Mr. Henry G. Kittredge.

At the beginning of the year the Associate Membership was 339. Of this number one has died, nine resigned; twenty-five have, however, been elected, making the present membership 354.

During the year the Society has suffered the loss of one of its oldest members, Mr. Thomas Gaffield, who served on the Executive Committee from 1879 to 1883. Mr. Gaffield's interests were not confined to the welfare of the SOCIETY OF ARTS alone, but also

to the Institute, as evinced by his gift of books, specimens of glass and minerals to the Departments of Geology and Chemistry. At the time of his death he was a member of the Corporation of the Institute.

No change has occurred in the management of the TECHNOLOGY QUARTERLY. Since the last Annual Report twenty-five articles have been published. Probably the most notable of these is one on the "Eclipse Expedition of the Massachusetts Institute of Technology to Washington, Georgia, under the direction of Professor Alfred E. Burton." Illustrating this article is an excellent photogravure reproduction of one of the best photographs of the sun's corona that has ever been taken. This article has been followed by one from the Rev. Professor William F. Rigge, S. J., who also observed the eclipse at Washington, Georgia, being in charge of a party from Creighton University, Nebraska. In this paper Professor Rigge makes an interesting comparison between his results and those obtained by the party from the Institute, all of which redounds to the credit of both parties. Professor W. O. Crosby has contributed two articles giving the results of his explorations of the sites of proposed water supplies for New York and Brooklyn. A gratifying instance of the loyalty of our alumni is furnished by the frequency of the contributions of two graduates of the Institute, Messrs. George C. Whipple and Daniel D. Jackson. They are actively engaged in investigation of problems connected with the biology and physical characters of the water supplied to towns, and have contributed four articles on different branches of this subject. Among other articles from the Physical Department are a series of tests, made by Professor Norton, on Fire Retardent Materials, and a series on Diffusing Glass of various kinds used in windows; and from Mr. William Lincoln Smith an extensive series of tests of Certain Shades and Globes for Electric Lights as used in Interior Illumination. From the Mechanical Engineering Department the usual annual contribution of Tests Made in the Engineering Laboratories was published in the September issue. Professor Fay and Mr. Badlam contributed an important article on the "Effect of Annealing upon the Physical Properties and the Microstructure of a Low Carbon Steel;" and the "Review of American Chemical Research," contributed by a number of members of the Chemical Department, has appeared regularly in each issue. Beginning with the current volume, a change has been made in the paper used in printing the QUARTERLY, and it is hoped that some saving of expense will result.

Respectfully submitted,

(Signed) GEORGE W. BLODGETT.
EDMUND H. HEWINS.
CHARLES T. MAIN.
JAMES P. MUNROE.

The Secretary read a communication from the Committee on Nominations, in which the following gentlemen were named as candidates for the Executive Committee for the year 1901–1902: George W. Blodgett, Desmond FitzGerald, Edmund H. Hewins, Charles T. Main, James P. Munroe. Mr. Blodgett announced that the Executive Committee had nominated George V. Wendell to be candidate for the office of Secretary.

A ballot having been taken, the Chairman announced the election of the above-named candidates.

Mr. Henry G. Kittredge, Industrial Editor of the *New York Commercial*, was introduced and gave an illustrated lecture on "Cotton from Seed to Bale."

"Thus far the Southern States of the United States have shown themselves to be the most extensive region and the best adapted for the growth of cotton of any in the world. No country has such an excellent river system and climate for the growth of this staple in its highest state of perfection. The cotton area of the Southern States is about 400,000 square miles, or about 250,000,000 acres, of which about 25,000,000 acres are now devoted to the cotton plant. This is at the rate of one acre in every ten. Rather than to increase this acreage, it would seemingly be better to intensify the culture of cotton by means of fertilizers for a larger yield. The meteorological conditions of the South must be taken as the standard for the world for the cultivation of cotton. The average temperature of the Southern States during the cotton-growing season is about 75°, while the relative humidity during this period ranges from 65° to 80°, and the rainfall amounts to 48 to 50 inches in the course of the year, with the dryest period during the growth of the plant. In order to secure the best results for length of staple, fineness of fibre and yield, great care must be taken in the proper selection of seed for planting and great care exercised in cultivation. More attention is given to the selection of seed in the planting of sea-island than in the upland varieties of cotton, though increased attention has been given to the latter in recent years. The system of cultivation varies in different parts of the South, depending upon the character of the soil and drainage. Among the diseases that affect the plant none has shown so much obstinacy as that known as the 'wilt.' This disease is not thoroughly understood, and no universal remedy is known for its complete eradication. It would seem to arise from the soil, where it lingers for a number of years. Hybridization is important in bringing cotton to a proper standard, which, after being attained, can be held only by careful selection of the seed for propagation."

The thanks of the Society were most heartily given to Mr. Kittredge for his instructive address.

GEORGE V. WENDELL, *Secretary.*

GEOLOGICAL HISTORY OF THE HEMATITE IRON ORES OF THE ANTWERP AND FOWLER BELT IN NEW YORK.

By W. O. CROSBY.

THE occurrence in specimens of the massive red hematite from the old Sterling iron mine near Antwerp, in Jefferson County, New York, of more or less pyrite and possibly pyrrhotite, in addition to the well-known pockets lined with crystallized siderite, chalcodite, specular hematite, and quartz, and further adorned by the brilliant golden needles of millerite for which this mine is famous, long ago suggested to me, as, perhaps, to others, that the hematite has had its origin in the differential oxidation of slightly nickeliferous iron sulphides, the nickel having remained in combination with the sulphur and recrystallized as millerite. But when in the summer of 1895 I visited the Sterling Mine, in company with Captain Hodge, an intelligent resident of Antwerp and for many years superintendent of the mine, and a party of students, I was surprised, not having previously read up on the geology of the mine, to find that the ore occurs in, and in intimate association with, a massive, soft, greenish-black, chloritic-looking rock, which is divided in all directions by slickensides and appears to be a highly altered (chloritized) trap. This rock was called serpentine by Ebenezer Emmons.[1] In part it bears some resemblance to serpentine, but in general the aspect is chloritic rather than serpentinic. Being fresh from the study of the deposits of nickeliferous pyrrhotite and chalcopyrite in the dioritic rocks of the Sudbury district in Ontario, and of the Gap Mine in Lancaster County, Pennsylvania, which had been quite clearly shown by Kemp and others to be products of magmatic differentiation, I at once adopted this as a provisional explanation, or working hypothesis, for the deposits of the Sterling Mine, and probably of the

[1] Geology Second District, pp. 93-96.

other mines of the Antwerp-Fowler belt, Captain Hodge having assured me that the geological conditions were similar throughout this linear series of deposits.

At the time of my visit, all of these mines had been closed for some time, probably never to be reopened; but my observations on the surface, including the dumps, supplemented by such information concerning the underground conditions as the superintendent could give me, led me to the conclusion: that the ore-body of the Sterling Mine is in a dike, 50 feet or more in width, of some highly altered basic rock, possibly diabase; that the ore was originally a magmatic segregation of this rock, chiefly in the form of sulphides, which have subsequently suffered more or less complete oxidation to a considerable depth, the ore being now, virtually, a gossan; and that this dike is, probably, continuous for the entire length of the belt of mines, although absolute continuity is by no means essential to the hypothesis.

The trend of the ore-belt and the hypothetical dike is approximately northeast from the vicinity of Antwerp, closely following the valley of a tributary of the Oswegatchie River. At the Sterling Mine, two and one-half miles from Antwerp, the southeast side of the valley is gneissoid granite, and the northwest side is Archæan limestone. The granite is of a distinctly acid type, of a light gray color and medium texture, rich in quartz and decidedly poor in ferromagnesian minerals — chiefly biotite; but with slight pegmatitic developments of only moderate coarseness. The granite appears to form the southeast wall of the dike, and the limestone, in a general way, the northwest wall, except that in the immediate vicinity of the mine the dike is, superficially, bordered on the northwest side by an outlier, probably of no great thickness, of the Potsdam sandstone. The descriptions of the mines by Putnam, in the *Tenth Census Report* (Vol. XV, pp. 141–144), indicate that the sandstone is a fairly constant feature of the deposits, occurring also at the Shirtleff Mine in the town of Philadelphia, which is not in the trend of the Antwerp-Fowler belt, and probably represents a distinct dike or occurrence of the chloritic rock and its associated ore. In most cases, however, the sandstone, which is still approximately horizontal, is described as covering the chloritic rock and ore more or less completely, suggesting that this basic igneous rock may antedate the sandstone, which was spread by the Potsdam sea across its outcrop; and certainly

the extreme alteration of the chloritic rock is indicative of a high antiquity. But, on the other hand, I have observed nothing in the composition of the sandstone as developed at the Sterling Mine confirmatory of the view that it was deposited over the ore-bearing formation. It is equally true, however, that it contains little or no identifiable detritus from the Archæan granite, for it is the clean, white, quartzose sandstone of fine and even texture so characteristic of the base of the Potsdam; and its composition harmonizes readily with the hypothesis that it is the newest rock in the section, as indicated by its horizontal attitude, if we accept the view developed in my study of the Archæan-Cambrian contact in Colorado,[1] that the transgression of the Potsdam sea over this area was so slow and gradual that erosion had time to accomplish its perfect work, base-leveling the surface and reducing all detritus to the two final terms — fine quartz sand and clay. Under these conditions sediments will rarely reflect in any reliable manner the mineralogical character of formations which they cover unconformably.

Unquestionably, the interest of the geology of the Antwerp-Fowler mines centres in the nature and origin of the chloritic rock and its true relations to the ores. On returning to Boston with my collection, I found that in the previous year (1894) Professor C. H. Smyth[2] had expressed the opinion, based upon microscopic and chemical examinations, that the chloritic rock is a highly altered phase of the granite. The fact upon which he especially relies is the occurrence in the chloritic rock of glassy grains and masses of quartz, which are regarded as residual. His analysis of a specimen free from visible quartz shows: SiO_2, 30 per cent.; MgO, 11 per cent.; FeO, 27 per cent.; and H_2O, 12 per cent.; the remaining 20 per cent. being, presumably, chiefly Al_2O_3. This is approximately the composition of prochlorite, and indicates an ultra-basic rock; while the granite, as represented by my specimens, is rich in quartz and poor in ferro-magnesian constituents, and certainly contains as much as 70, if not 75, per cent. of silica.

The general aspect of the rock is precisely that of many highly chloritized traps in the vicinity of Boston; and this resemblance is heightened by the slickensides, by which it is minutely and almost

[1] Bull. Geol. Soc. Amer., 10, 141–164.

[2] Bull. Geol. Soc. Amer., 6, 4.

indefinitely subdivided (Figure 1). These testify to differential movement throughout the mass, and can have, apparently, but one explanation — expansion due to chloritization and hydration. It is manifestly impossible to find in this light-colored, acid granite more than a small fraction of the magnesia and ferrous oxide shown by Professor Smyth's analysis of the chloritic rock. They are clearly not chiefly residual constituents of the granite; and if his hypothesis stands, the main

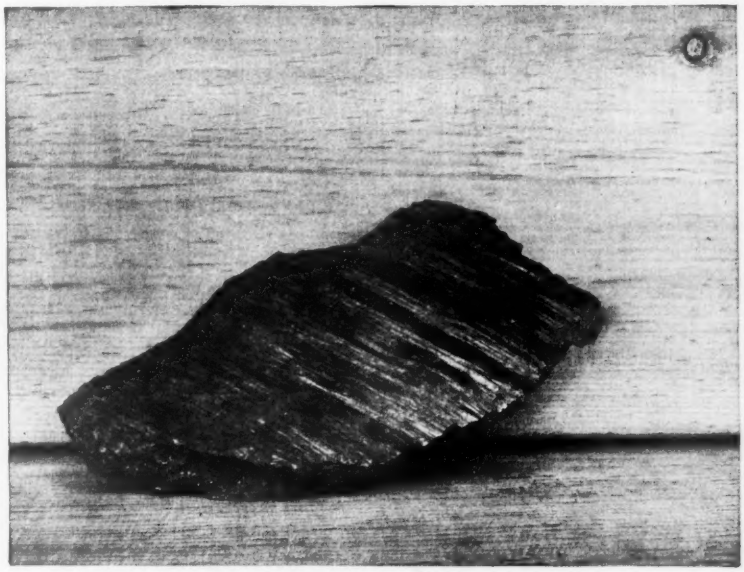


FIG. 1. — A fragment of the chloritic rock, showing slickensides. Two-thirds natural size.

part of each must be imported. The only alternative is to suppose that the silica and alumina have suffered a highly improbable diminution, in which case the expansion of the rock essential to the explanation of the slickensides would be unexplained. But where can we find an adequate external source of the MgO and FeO? Professor Smyth suggests the Archæan limestone and the action upon it of solutions derived from the oxidation of some near-by deposit of pyrite. But no sulphides are known in the vicinity, except those intimately associated with the hematite in the chloritic rock; and it is not apparent by what reactions the magnesia of the limestone, existing,

probably, largely in the form of insoluble silicates, is to replace the acid aluminous silicates of the granite, reducing the silica by fully 40 per cent. Professor Smyth seems, further, to regard the ore as a replacement of limestone, although so intimately associated with and enclosed in the massive chloritic rock, which is interpreted as an altered phase of the granite. The masses of crystalline calcite in

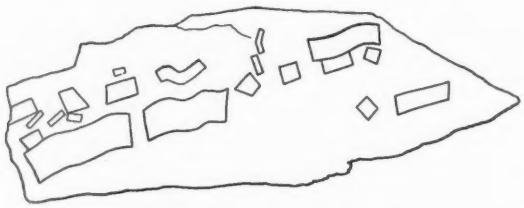


FIG. 2. — A fragment of the chloritic rock showing, diagrammatically, stretched and dislocated veinlets of quartz. One-third natural size.

the ore are certainly suggestive of inclusions of limestone; but it is important to remember that calcite is an exceedingly common secondary mineral of the basic eruptives, as witness the crystalline calcites of the cupriferous melaphyrs of Keweenaw Point.

Apparently, the chemical difficulties of Professor Smyth's thesis are insuperable; but we turn now to the consideration of his main argument — the disseminated grains of quartz in the chloritic rock. To begin with, the free silica or quartz appears to be wholly or almost wholly wanting in a considerable portion of the chloritic rock; and it is probably this material that is represented by Professor Smyth's analysis. A considerable part of the quartz, also, occurs, or has occurred, in the form of veinlets, varying from a line to possibly an inch or so in width. Although undoubtedly secondary features of the rock, the veinlets clearly antedate the final or complete alteration; and especially do they antedate a large part of the hydration, expan-

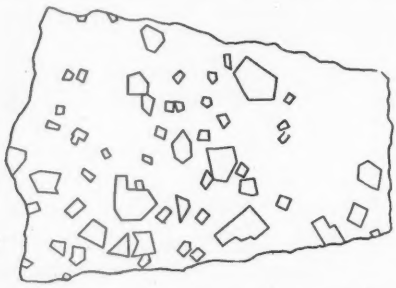


FIG. 3. — Another fragment of the chloritic rock showing, diagrammatically, angular inclusions of quartz, the most of which, at least, are probably due to the comminution of quartz veinlets. One-half natural size.

sion, and consequent slickensiding of the mass, for they have been very extensively broken, dislocated, and even granulated by this differential movement. The chloritization or greenstone alteration of a trap, it is well known, involves the liberation of a large amount of silica, which commonly takes the form of veinlets in the rock, and then during the later stages of the alteration the veinlets may be broken and disarranged. How complete the destruction may be is well shown by Figures 2 and 3, drawn from specimens collected on the dump of the Sterling Mine. The included areas are wholly glassy quartz; but a part of that shown in Figure 3 may not be vein quartz, although the main part of it certainly is, as indicated by the large size and distinctly fragmental forms of the masses. In no instance does the chloritic rock itself, apart from the included quartz, appear to have been crushed or brecciated; but the slickensides suggest, rather, a differential flowing which has brecciated the unyielding quartz veinlets. It is easy to see, in the light of these examples, that with slender veinlets, at least, a complete and seemingly original granulation of the quartz might result. Again, the secondary silica in a case of this kind does not necessarily assume wholly the form of veinlets, but it may have been developed in part as amygdules or pseudo-amygdules, or as irregular segregations and replacements. Certain it is that a trap rock is, during the process of chloritization, a prolific source of free silica, which is unlikely in the case of a large dike to escape wholly, even into cracks in the rock itself, crystallizing in part in interstitial or disseminated forms.

I have not observed the masses described by Professor Smyth as showing gradation from the granite into the chloritic rock or greenstone; but not having read his paper before visiting the locality, I may have overlooked them. I venture the suggestion, however, that they may be inclusions of the granite in the basic dike, which have naturally shared the alteration of the latter and are by simple contact more or less stained or impregnated by the chloritic material. Of course, this might happen to the unbroken granite wall of the dike as well as to inclusions. As showing that granitic inclusions are not wholly wanting, I may add that my collection from the Sterling Mine contains a mass of a distinctly pegmatitic character, in which coarsely crystalline mica is a prominent feature, which I broke out of the soft, dark-green, chloritic rock. It does not, however, show any important alteration, even the mica being still essentially intact. The sandstone

on the opposite side of the dike, although of a distinctly permeable character, does not, so far as I have observed, show any appreciable chloritic impregnation, notwithstanding the fact that it is at some points very deeply stained or impregnated, but not replaced, by the hematite.

As additional evidence that the quartz in the greenstone may be secondary rather than residuary may be mentioned the crystalline quartz occurring with the siderite, chalcodite, millerite, etc., in the

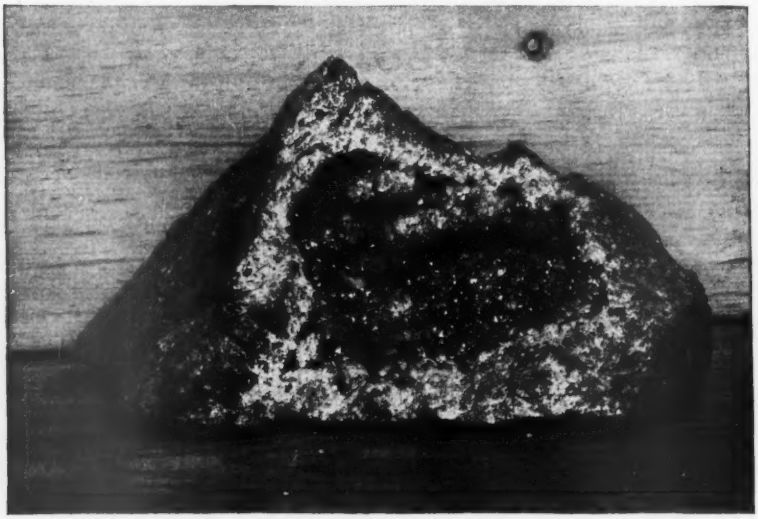


FIG. 4. — An angular quartz geode, due to the replacement of a joint-block of the chloritic rock. About one-third natural size.

pockets of the hematite; and the fact, well attested by specimens in my collection, that the greenstone has been metasomatically replaced by quartz on a considerable scale. One specimen shows the complete replacement of an angular joint-block of the greenstone nearly a foot long and half as thick, forming a sharply angular quartz geode of these dimensions (Figure 4). Even granting that the granular quartz is partly or wholly residuary does not prove the derivation of this ultra-basic rock from the granite, for the original basic rock of this dike may very well have been quartziferous, a quartz-diorite, or possibly a quartz-gabbro. The original rock, while quite certainly not so acid as the granite, was not necessarily highly basic; and the

magmatic segregation of sulphides is by no means confined to rocks exceptionally low in silica; but it is fairly common in rocks of neutral or sub-acid character, and even, as in the case of some of the ore-bearing dioritic rocks of the Sudbury district, in those containing free quartz.

In view of all these considerations, it appears to me most probable that the chloritic rock or greenstone is a highly altered, basic eruptive; although I recognize that some facts point to its derivation from the granite, and especially that the disseminated granular quartz would find thus its readiest explanation. Again, a basic dike six miles or more in length appears far more probable than a sharply defined and apparently persistent zone of granite showing such a radical and unusual transformation as the alternative hypothesis calls for, especially as such a zone of alteration, while unique, and on chemical lines, at least, highly improbable for the granite, is entirely normal for the dike. In other words, if the basic dike be granted, the development of the sulphides in it by magmatic segregation, the chloritization of the silicates while still at a great depth, and the subsequent development of the iron ore by the differential oxidation of the sulphides, appear as entirely normal incidents of its history.

I may add to this that some of my specimens from the Sterling Mine show sulphides, still unoxidized, disseminated in the slickensided chloritic rock precisely as in the diorite of the Sudbury mines and of the Gap Mine; and in this connection it is interesting to note further, that, according to Brooks [1] and several of the sections given by Emmons, the normal position of the iron ore is, more or less distinctly, peripheral with reference to the chloritic rock, thus paralleling another important feature of the deposits having their origin in magmatic segregation.

Since writing this paper, I have had an opportunity to study some of the auriferous veins of the new Michipicoten District of Ontario; and I was specially interested in an occurrence on the southeast side of Lake Wawa, where, during the alteration of a basic dike, the resulting chloritic matter has impregnated and saturated the bordering acid granite to such a degree that the latter rock is completely disguised, the granite falling under the hammer into thin, angular fragments, which are completely coated with the shining, black, chloritic glaze, and being easily mistaken for a chloritized trap.

[1] Am. Jour. Sci., 3d series, Vol. IV., pp. 22–26.

Closer examination shows, however, that the original minerals of the granite are but little altered; and that it is essentially a case of the saturation of a rock along joints and rifts by the secondary mineral of a neighboring rock. This appears to throw some light upon the problem of the quartzose chloritic rock of the Antwerp-Fowler iron mines, and at least suggests the possibility that the quartzose portions of this matrix of the iron ore may be, after all, a phase of the granite. But the basic dike is still required as a source, alike of the impregnating chloritic matter and of the metallic contents of the formation.

GEOLOGICAL HISTORY OF THE CHARLES RIVER.

By FREDERICK G. CLAPP.

Received July 8, 1901.

Introduction.

One of the most interesting streams of Massachusetts is the Charles River, the basin of which occupies a large part of Suffolk County, the western and northwestern portions of Norfolk, a small portion of Worcester, and a strip along the southeastern part of Middlesex County, and includes the whole or considerable portions of twenty-eight cities and towns.

This river is of the utmost importance to the inhabitants of eastern Massachusetts. From its source, in the town of Hopkinton, to its mouth, in Boston Bay, it has a total length, following the meanderings, of sixty-nine miles, and its drainage area is about 290 square miles. Distributed along the river are twenty-six artificial dams, aggregating in height 202 feet, which serve as water power for numerous factories and mills; and one of the dams, in Hopkinton, retains the water supply of the town of Milford. Five other towns — Newton, Brookline, Waltham, Wellesley, and Watertown — obtain their water supply in whole or in part from filter galleries in connection with the river. The tidal portion of the stream is navigable for several miles above its mouth, enabling easy communication with several important manufacturing and other establishments. Picturesque portions, such as Hemlock Gorge, and also stretches lower down on the river, are held by the Commonwealth as public parks. And it is proposed by the Metropolitan Park Commission to improve long stretches of the banks between Dedham and Boston for the public benefit. The tidal portion of the river, between Boston and Watertown, furnishes an exceptional opportunity, by constructing a dam at the proper place, for forming a water park which would be a very valuable addition to Boston's park system. I feel that the present

discussion of the history of the river is especially timely on account of the recent agitation to secure legislation for such a park.

It is impossible to look at the Charles River as represented on the map (Plate 1) without noticing its extremely circuitous course. Rising in the town of Hopkinton, it flows for the first few miles almost directly south. But at Bellingham it bends abruptly to the east, and then to the north, taking a retrograde course as far as West Medway. From this point it runs east as far as Rockville, north and then northeast to Sherborn. Taking a northerly course to South Natick, it there turns to the east, as if to make a short cut to the sea; but at Dedham it bends sharply backward, and flows directly away from the sea as far as Newton Lower Falls, from which point it runs north to Waltham, and then east to its mouth in Boston Bay. Instead of having a length of twenty-five miles, as it would if it ran northeast from its source straight to Boston Bay, the river flows nearly three times that distance. Its transverse meanderings cover a northwest-southeast distance of eleven miles.

In conducting the studies represented in this discussion, the principal purposes kept in mind have been the following:

First.— To give as complete a history of the life of the river as possible.

Second.— To explain why the river follows its present devious course rather than a more direct one. For instance, why does it bend north at Bellingham, instead of continuing southward to Narragansett Bay, the shortest course to the sea? Why, when it has followed a northeasterly course for a dozen miles, does it bend suddenly to the northwest, instead of continuing across Medfield to Boston Bay? Why does it not follow a direct course across Wellesley to Riverside, a distance of three and a half miles, rather than the actual course of seventeen miles by way of Dedham? Again, upon reaching Dedham, why does it not flow straight to Boston Bay, instead of bending back towards Newton?

Third.— To trace the past courses of the river and the causes of the various stages in its development.

Fourth.— To explain the relations of the river and its system to the geological structure of the region, and to determine the causes for such relations.

Fifth.— To determine to which of the recognized classes of rivers the Charles belongs.

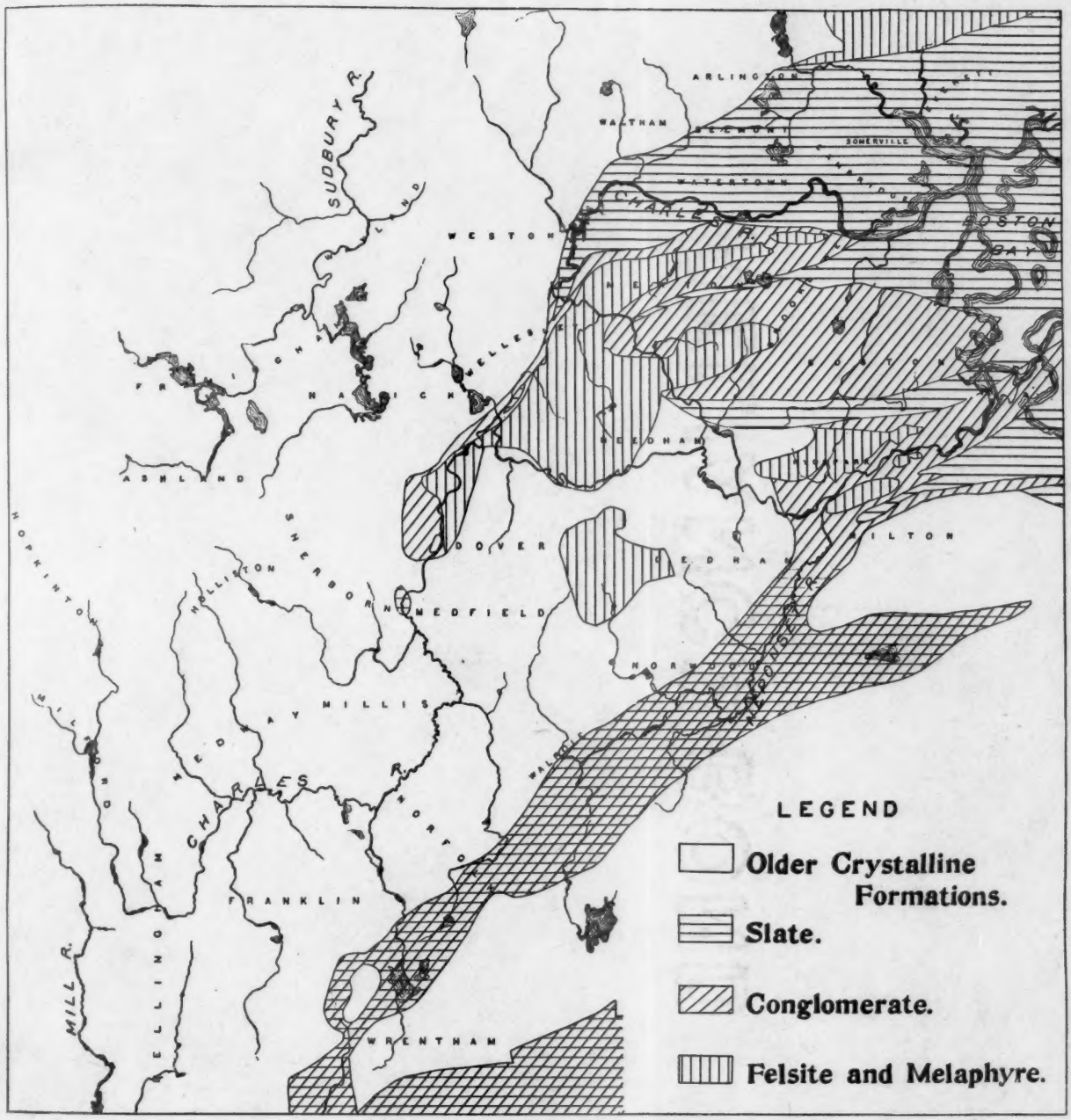


PLATE I. — GEOLOGICAL MAP OF THE CHARLES RIVER BASIN AND VICINITY. SCALE, 1: 250,000.

The work undertaken in following out these designs has been mostly done on foot in the field; but besides, I have endeavored to gain access to all recorded information bearing on the subject, and I take pleasure in acknowledging my indebtedness to those who have been of assistance to me in obtaining it: to Professor W. H. Niles, for advice in various ways; to Professor G. H. Barton, for the loan of maps; and to Professor W. O. Crosby, for the use of maps and for much valuable information. For records of bench marks, depths of bed-rock and elevations, I am indebted to the gentlemen connected with the various state and town boards, the Metropolitan Park Commission, the Harbor and Land Commission, the water boards of Boston, Waltham, Newton, Wellesley, and Brookline, and the engineering department of the New York, New Haven & Hartford Railroad. Messrs. B. F. Smith & Brother, Morton & Waugh, and E. A. Clarke have furnished valuable information concerning artesian wells in Boston and vicinity. A list of the various works consulted will be given in the appended Bibliography.

General Description of the Region.

The government topographical map shows that along the western margin of the river basin south of Ashland there extends a high ridge of land having an elevation of from 300 to 600 feet, and forming a natural boundary to the basin. A second, less marked ridge, runs from north to south between Medway and Milford, descending towards the south to the level of the river. With these two exceptions, the highest hills in the Charles River basin rise to elevations of between 300 and 460 feet. As Professor Crosby has shown, the few rock hills of these heights in Eastern Massachusetts are remnants of the Cretaceous peneplain. Between them the Tertiary peneplain is developed, having an elevation of from 100 to 200 feet; and in this less perfect plain the valleys of the Charles and its tributaries have been carved.

The source of the brook which is considered the head of the river is at an elevation of about 500 feet. As is shown by the profile on Plate 2, the descent in the upper part of the stream is very rapid. It crosses the 400-foot contour but one mile, and the 300-foot but two miles, from its source. The 200-foot contour is crossed at Bellingham, twelve miles from the source, and the 100-foot below Natick, about midway in the length of the river. Looking at the profile more

in detail, several points are noticed where the fall is concentrated. At Medway there is a descent of 27 feet in a distance of half a mile. The descent at Newton Upper Falls is 25 feet in a quarter of a mile, and at Newton Lower Falls 22 feet in about the same distance. Between these points of rapid fall there are long stretches where it is very slight indeed. Two of these stretches, one between Rockville and Natick, and the other between Charles River Village and Newton Upper Falls, are especially noticeable.

A great difference exists in the size of the river valley in its different portions. In general, the depression forming the main valley is very broad, but it will be noticed that at several points, as at Medway and at Sherborn, the highlands follow both sides of the river closely for some distance. Especially important are several prominent gaps in the watershed between the Charles and adjacent basins; for example, at Bellingham, Walpole, and Cochituate.

The geological structure of the region is shown in Plate I. It will be seen that the river basin is located in the vicinity of three areas of sedimentary rocks, those of the Boston, Norfolk, and Narragansett basins. These basins are occupied mostly by Carboniferous strata — slates, sandstones, conglomerates, and lavas — which are much softer than the older crystalline formations, the granites, diorites, and felsites, which occupy most of the remainder of the region. For this reason the Carboniferous areas have been worn down, in general, to much lower levels than the harder, crystalline areas (see topographical map).

Outline of the Geology of the Region.

The following discussion will be simplified by giving first a brief outline of the geological history of the whole region since Mesozoic time. During the Cretaceous period the land stood at a level several hundred feet lower than at present, and by long-continued action the sea cut gradually backward, forming the Cretaceous peneplain.[1] As the encroachment continued, sediments formed by marine erosion were spread over the entire submarine surface of the region.

At the close of the Cretaceous period an elevation of the land took place, raising the peneplain with its burden of Cretaceous sediments

[1] W. O. Crosby: Geological History of the Nashua Valley During the Tertiary and Quaternary Periods, TECHNOLOGY QUARTERLY, Vol. XII, No. 4, p. 289; Geology of the Boston Basin, Pt. 3, p. 538, *Occasional Papers*, Boston Soc. Nat. Hist.

out of the water. From the new land surface thus formed, the streams must have run off, taking the shortest courses to the sea, and utterly regardless of the structure of the underlying harder rocks. At first they flowed upon the unconsolidated Cretaceous sediments; but after these were completely removed by erosion, the solid rocks beneath were attacked, and the formation of a second, the Tertiary peneplain,[1] commenced.

The streams at the time of the Cretaceous elevation were original and consequent upon the slope of the land. As by continued erosion the Cretaceous sediments were entirely removed, the streams became superimposed upon the underlying hard and soft formations. The basin rocks, being least resistant, were removed more rapidly than the outlying crystallines, and the streams gradually shifted their courses on to the softer rocks. Thus they became adjusted, during the Tertiary period, to run in the basins as much as possible. The streams rising on the crystalline areas must have been so adjusted as to take the most direct courses to the basins.

Near the close of the Tertiary period a great elevation of the land occurred, probably amounting to several thousand feet. This increased the energy of the rivers, so that in the bottoms of their valleys they cut deep gorges, extending many miles above their mouths. The gorge at the mouth of the Charles is from 100 to 200 feet deep — below the present sea level. While the land stood at this elevation, the Glacial epoch came on, during which time the whole region was buried beneath the ice sheet, and was covered with a coating of bowlder clay which filled up the Pleistocene gorges and some of the Tertiary valleys. During the recession of the ice to the north, at the close of the Glacial epoch, many of the valleys were blocked by ice or drift, forming large glacial lakes, in which were deposited great quantities of sand and gravel. These overlaid the till in the lowlands and completely changed the character of the topography. Thus when new streams were formed they rarely took their former courses, but instead found new channels across the drift-covered surface in entire indifference to the preglacial conditions.

Preglacial Drainage of the Region.

In order to decipher the courses of the preglacial streams, I will endeavor, first, to show what portions of the present river valley are

[1] *Loc. cit.*

so youthful in their characteristics as to lead to the belief that they have been formed since the Glacial epoch, and then to determine the preglacial courses for these portions. From the fragmentary streams thus discovered, the entire preglacial system of drainage can be constructed with a considerable degree of certainty.

In order to facilitate discussion, it will be convenient to divide the main valley of the Charles into four parts, which can be done very readily on account of the topography. That portion of the river and its valley above Medway I will call the Upper Charles; that between Medway and Sherborn, the Middle Charles; and that below Sherborn, the Lower Charles. The fourth subdivision is the tide-water portion of the river. The sequel will show why these distinctions are made.

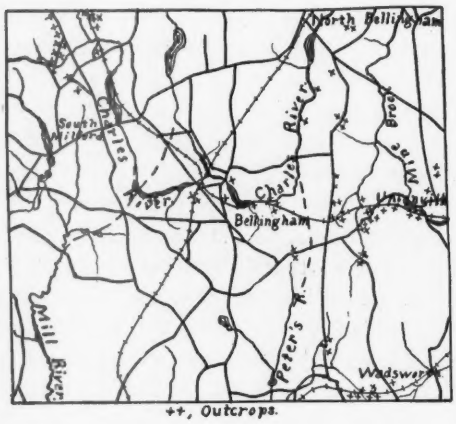


FIG. 1. — MAP OF THE VICINITY OF BELLINGHAM, SHOWING IMPORTANT OUTCROPS.

The Upper Charles. — Rising in the village of Hayden Row, Hopkinton, the river flows for the first ten miles almost directly southward. The valley south of Milford is broad and evidently old. South of Factory Pond it is occupied by an extensive sand-plain. But a mile south of Factory Pond a sudden bend occurs, and the river flows for two miles in an easterly direction. In this stretch the character of the topography is strikingly different from that in the north-south course. Between Milford and Bellingham Junction, with one or two possible exceptions, outcrops of rock nowhere occur within 500 feet of the stream; but below the bend the rock valley gradually narrows down, until, a mile below the Junction, rock approaches close to the river on both banks. The till slopes here come to within a quarter of a mile of the river. The locations of outcrops near the river are shown in Figure 1. On this and subsequent maps I have not attempted to represent all the outcrops, but simply those which concern the present discussion.

By studying Plate 2 it will be seen that while the amount of fall in the four miles above this section is 35 feet, here it is 19 feet in a distance of seven-eighths of a mile. This rate of fall continued for four miles would give 92 feet, showing a much more rapid descent here than directly above. These facts naturally lead to the suggestion that the river is here out of its preglacial course.

Emerging, northeast of Bellingham, from its narrow valley, the

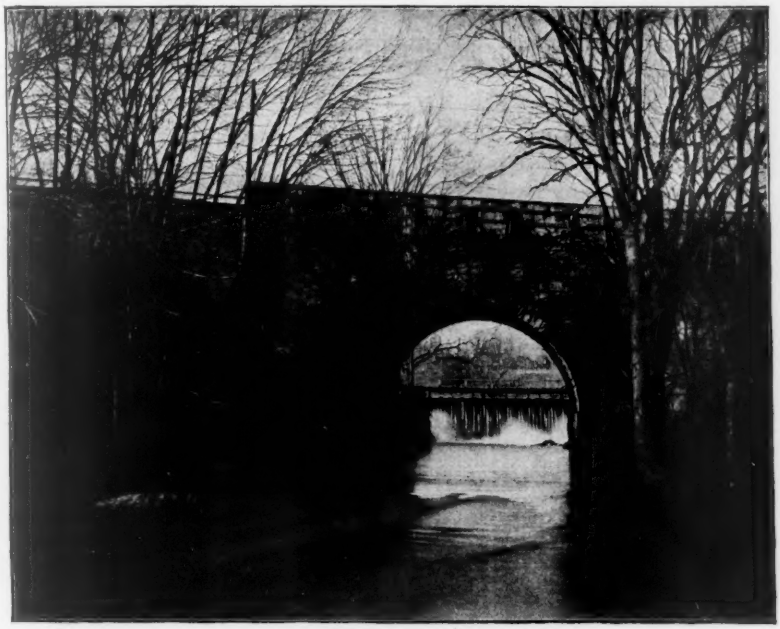


FIG. 2. — CHARLES RIVER AT SANFORD STREET, MEDWAY, SHOWING DAM BUILT AGAINST VERTICAL FACE OF ROCK.

river turns sharply to the north, and flows as far as West Medway through a broad valley, occupied above North Bellingham by meadows 500 to 2,000 feet broad, and having all the characteristics of being very old. Towards the north, however, it narrows, and at West Medway takes a more easterly course.

By referring to the topographical map it will be seen that a broad ridge of high land, overlaid by till, extends south from Holliston to beyond Kelly Street, Medway, within half a mile of the Charles.

South of the river the ridge rises rapidly to a maximum height of 320 feet, and extends southward beyond the limits of this study. Between these two portions of the ridge lies the Medway sand-plain. North of the village, on account of the great thickness of the plain, not a single outcrop is exposed. To the south, however, the river has cut a deep ravine down to the underlying rock, in which it has continued the work of erosion (Figures 2 and 3). Within a distance of half a mile three dams occur.

FIG. 3. — ROCK IN THE MEDWAY GORGE.

The slopes of the Medway sand-plain first approach the river just east of Shepard's Brook. Near this point, in order to pass the ridge of till and its underlying rock, the stream turns to the northeast. Half a mile above Sanford Street ideal erosion slopes rise north of the river to a height of from 60 to 80 feet. All evidences show that at the close of the Glacial epoch the recently formed sand-plain completely filled the half mile gap in the highlands, and in order to find an outlet to the east the stream has had to cut a new valley through the plain. It is here, as at Bellingham, out of its preglacial course.

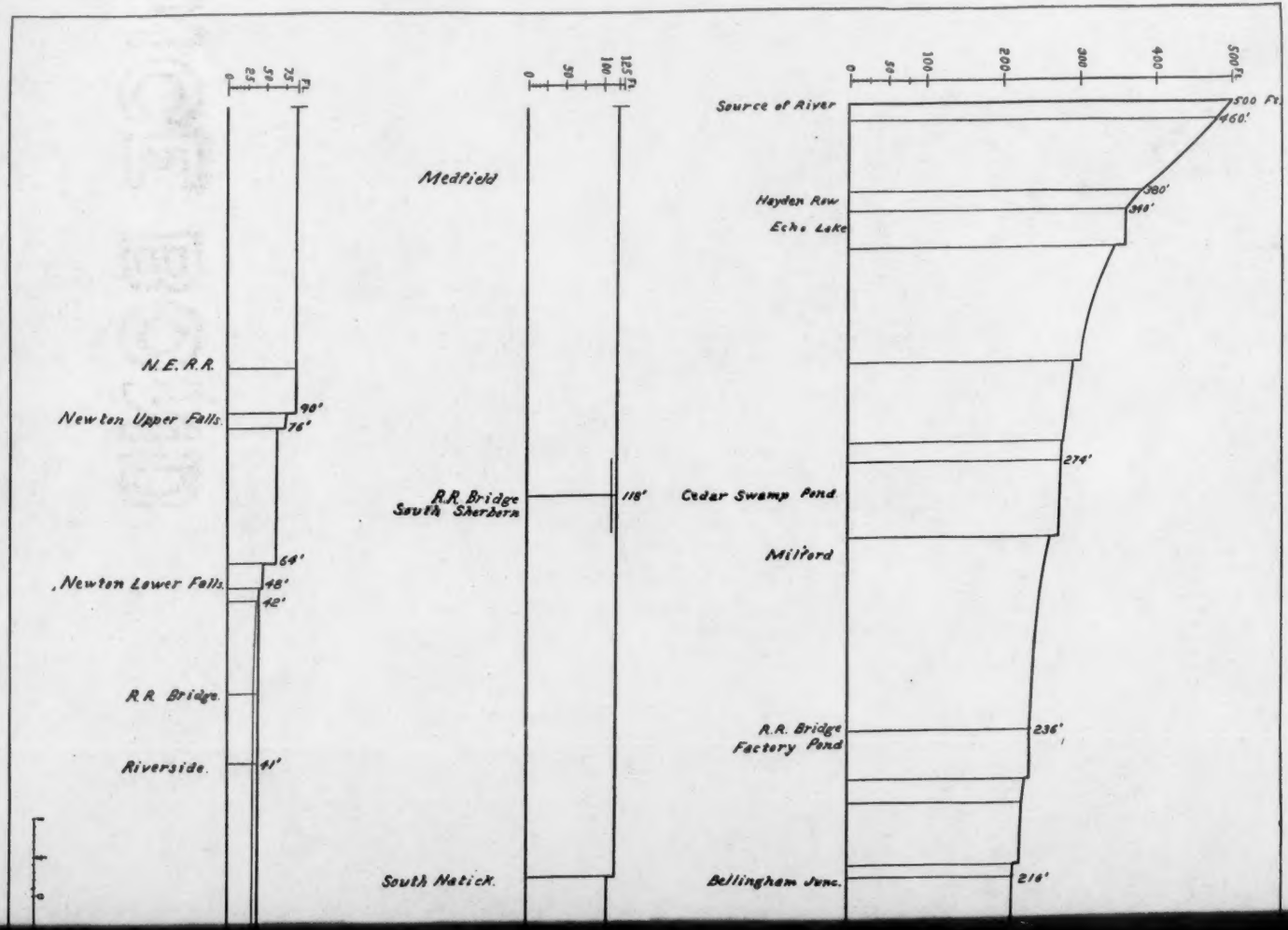

0
25
50
75 Ft.
N.E.R.R.
Newton Upper Falls.
90'
76'
64'
Newton Lower Falls.
48'
42'
R.R. Bridge.
Riverside.
41'
0
50
100
125 Ft.
Medfield
R.R. Bridge
South Sherborn
118'
South Natick.
0
50
100
200
300
400
500 Ft.
Source of River
500 Ft.
460'
Hayden Row
380'
348'
Echo Lake
274'
Cedar Swamp Pond
Milford
R.R. Bridge
Factory Pond
236'
Bellingham Junc.
216'

PLATE 2.—H

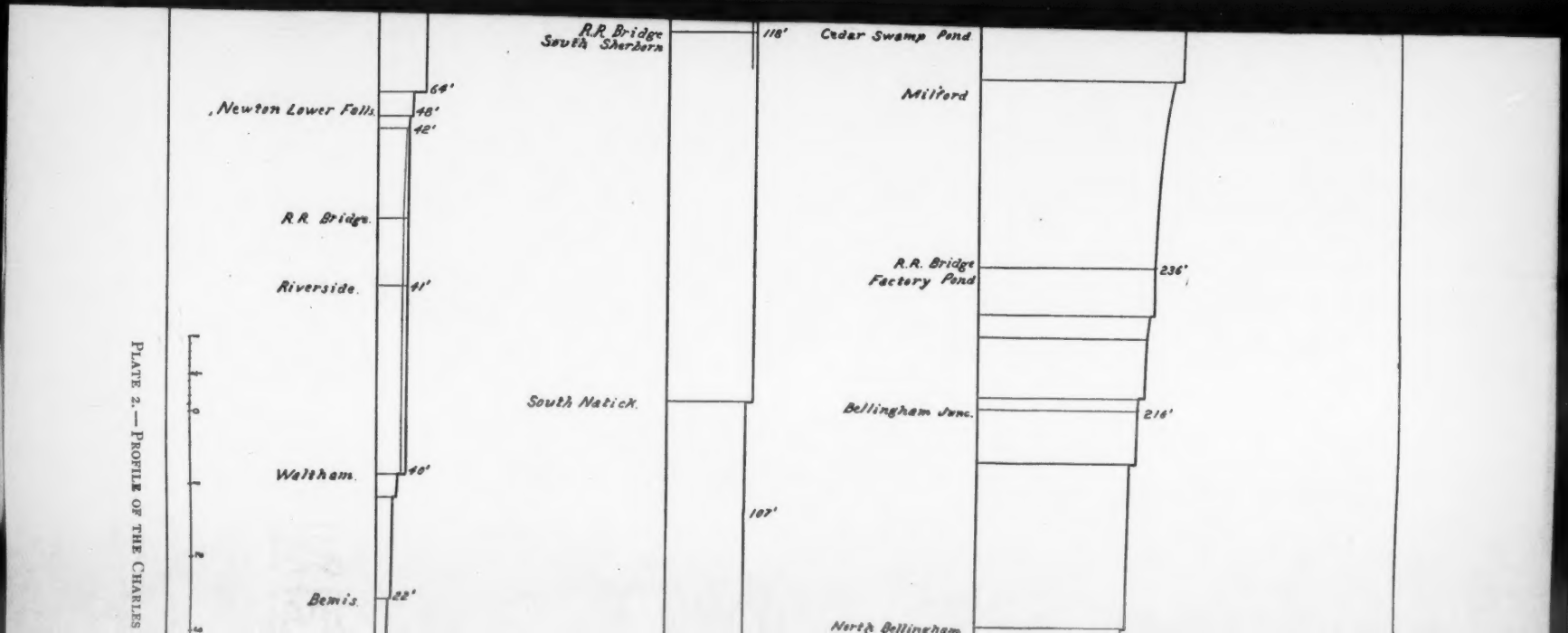
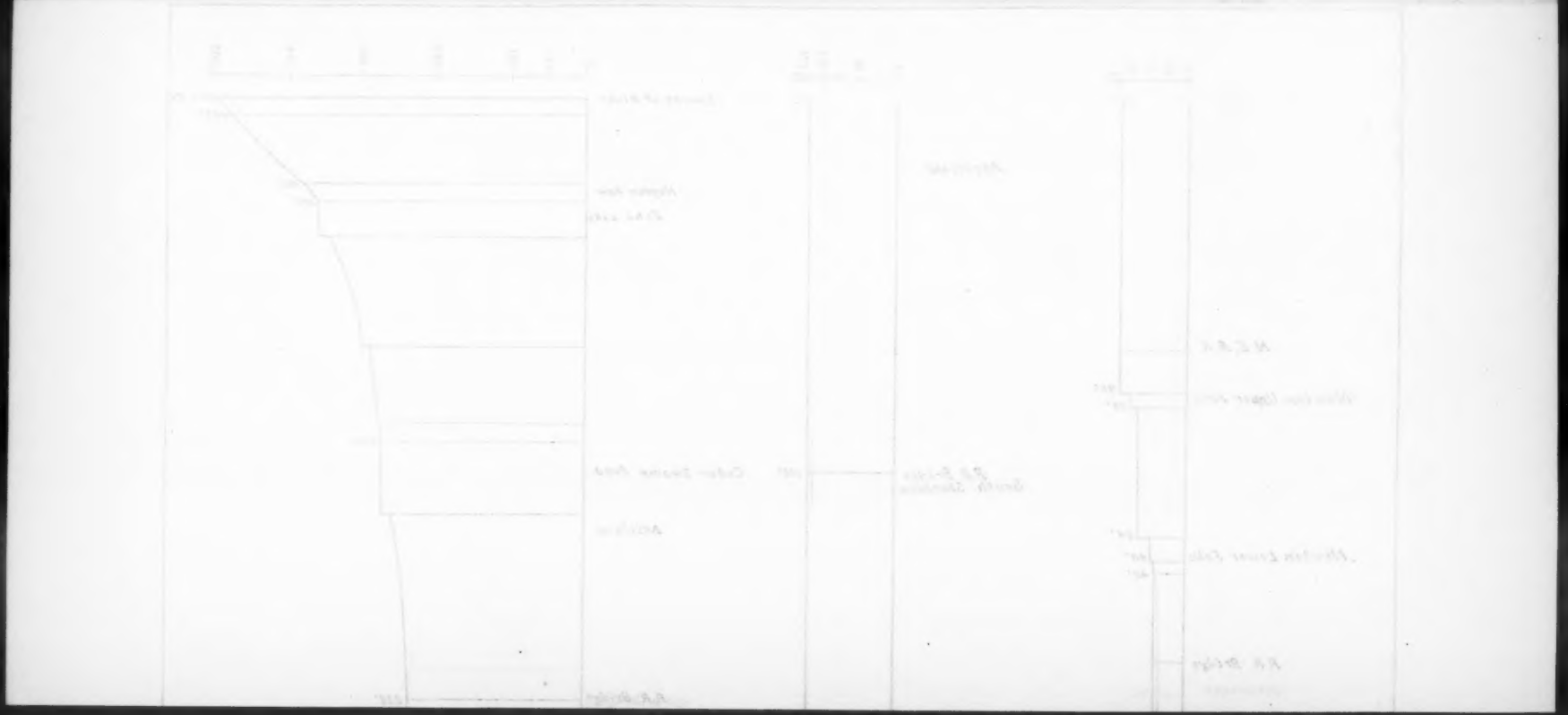


PLATE 2.—PROFILE OF THE CHARLES

THE CHARLES RIVER.



In searching for the former channel we have two alternatives: First — the river may have passed the ledges at Medway through a valley either to the north or south, which is now buried by drift. If to the south, it must have continued eastward from Shepard's Brook to Populatic Pond. The high ridge of till here, however, and the fact that ledges occur all along its northern end, and farther south are exposed on its summit, make it extremely improbable that any buried valley exists here. But if the preglacial valley was north of the present valley, it is occupied now only by modified drift. This course would be possible, but other conditions render it unlikely. It would be extremely improbable, if the Upper Charles flowed east across Medway in preglacial time, that its valley would now be obstructed by such a prominent and uninterrupted north-south ridge as actually exists here. These considerations lead to the natural inference that the underlying rock is continuous from Holliston to Franklin at such an elevation as to bar the way to any preglacial river.

If such is the case, the second alternative must be accepted — that above Medway the direction of the river has been reversed, and that previous to the Glacial epoch it flowed south instead of north; in which case there must be somewhere in the watershed of the Upper Charles a buried valley, the former outlet for the stream. Searching for such a valley, I found its most probable location to be the pass east of Bellingham, where the Charles approaches within a mile of the source of Peters' River, a tributary of the Blackstone. The broad pass at this point is occupied by a sand-plain, and is wholly destitute of outcrops for half a mile east and west (Figure 1). West of Bellingham, at the point where the Charles bends toward the east, there probably exists another buried valley, which in preglacial time furnished an outlet to Mill River. At this point the streams are less than a mile apart, and the watershed between them, in which no outcrops have been found, rises less than 40 feet above the Charles. Careful search has shown this to be the only likely preglacial outlet for the valley northwest of Bellingham. The probable ancient courses are indicated by dotted lines in Plate 3. To summarize, the reasons for believing that the Upper Charles was tributary to Narragansett Bay, as shown in the plate, are: —

1. The valleys both east and west of Bellingham point towards gaps in the watershed on the south.

2. The east-west valley at Bellingham possesses distinctly post-glacial characteristics.

3. The valley from North Bellingham through the gap in the watershed to South Bellingham offers a nearly straight course.

4. The valley south of Caryville is much broader than to the north, and the width increases towards Bellingham. Between Bellingham and Caryville it is too large to belong to a small stream flowing north from Bellingham, but it may easily have been formed by Chicken, Shepard's, Hopping, and Mine brooks combined.

5. The southward course is the shortest route to the sea, being only twenty miles from Bellingham to Narragansett Bay, while to Boston Bay it is twenty-seven miles.

6. The topography and geology in the vicinity of Medway render it improbable that any preglacial outlet existed in that direction. Thus the Bellingham outlet is left as the only alternative.

7. This course would follow the area of metamorphic rocks extending south from Medway. The present course, on the contrary, is from the metamorphic to the harder, igneous rocks.

The Middle Charles. — By referring to the topographical map of the United States Geological Survey, it will be seen that a marked ridge of high land crosses the Charles River basin from the watershed of the Neponset at Cedar Hill to the Charles near South Sherborn, and on the western side of the river crosses to the Sudbury watershed at Paul's Hill in Sherborn. Both north and south of Dover the basin of the Charles varies in width from thirteen to sixteen miles, but this line of highlands narrows it to about six miles (Plate 3). From this well-defined east-west ridge the streams flow off in either direction, giving it the character of a watershed, which, if the river did not run across it, would be a true divide, separating two distinct river basins.

On the eastern side of the river the area of high land is continuous, at elevations varying between 200 and 400 feet above sea level, from Cedar Hill to within a quarter of a mile of the Charles. East of South Sherborn outcrops occur, even down to the level of the river itself. At this point the stream is bounded on the west by a bold granite hill over 260 feet in height, which, just north of the railroad bridge, descends precipitously to the water. The line of steep cliffs extends round the eastern face of the hill for nearly a mile, to the point where the rock on the eastern bank comes close to the river.

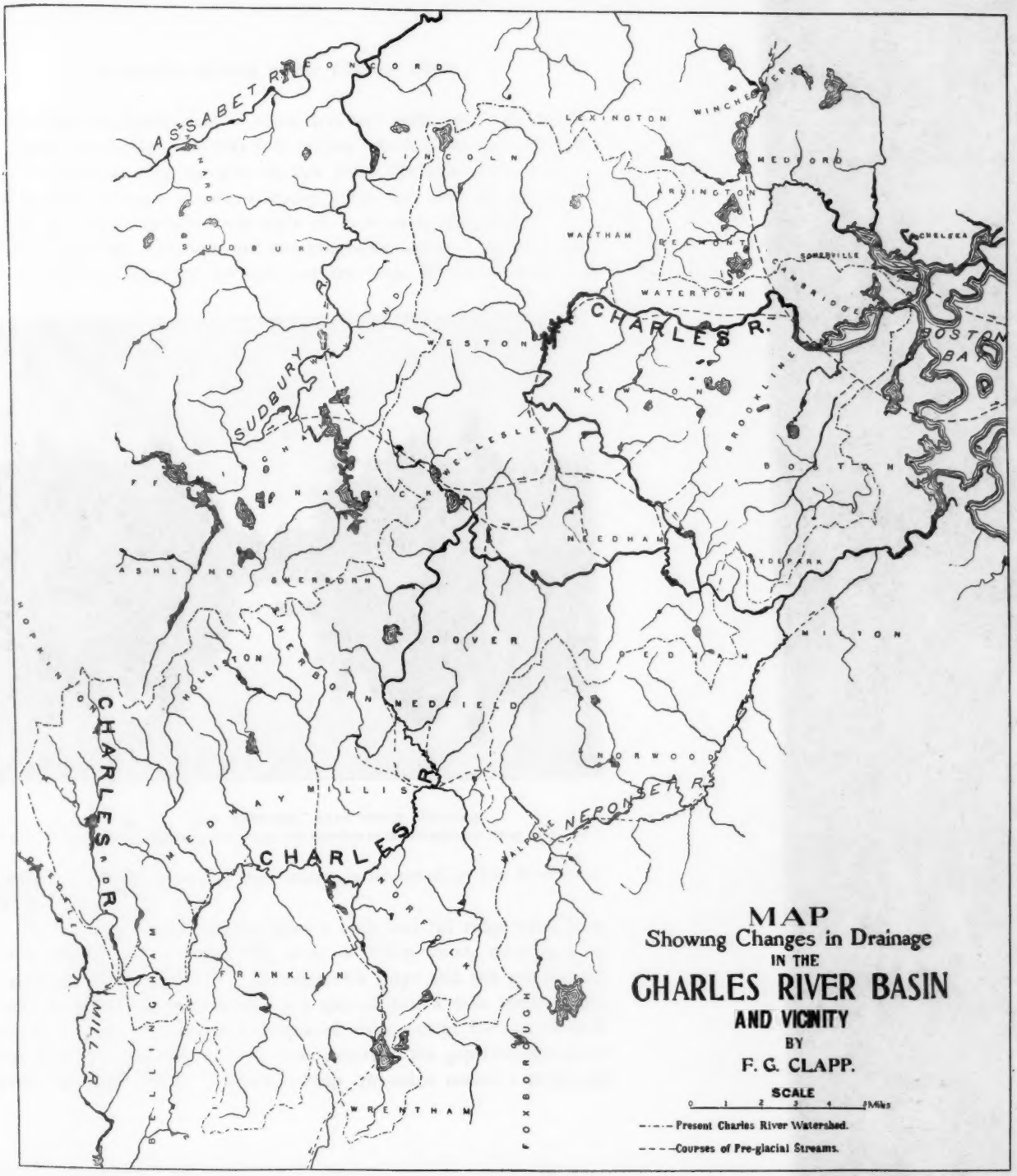

ASSABET R.
CONCORD
LINCOLN
LEXINGTON
WINCHESTER
MEDFORD
ARLINGTON
SUDBURY
WALTHAM
BELMONT
CHELSEA
SOMERVILLE
CAMBRIDGE
WATERTOWN
CHARLES R.
BOSTON BAY
WESTON
SUDBURY R.
NEWTON
BROOKLINE
WELLESLEY
NATICK
BOSTON
NEEDHAM
HYDE PARK
ASHLAND
SHERBORN
DOVER
MILTON
HOPKINTON
HOLLISTON
MEDFIELD
NORWOOD
CHARLES R.
CHARLES R.
MAYNARD
WALPOLE
NEPONSET R.
FRANKLIN
MILL R.
WRENTHAM
FOXBOROUGH
MAP
Showing Changes in Drainage
IN THE
CHARLES RIVER BASIN
AND VICINITY
BY
F. G. CLAPP.
SCALE
0 1 2 3 4 5 Miles
Present Charles River Watershed.
Courses of Pre-glacial Streams.

PLATE 3.

At this place the flood plain is some 400 feet wide, and is divided in the centre by a ledge, say 200 feet across, which rises over 20 feet above the marsh. On the east of this ledge the river flows with a rapid current through a narrow, rocky gorge not over 40 feet wide (Figure 4). The nearly vertical walls of rock rising directly from the water indicate that this was not the preglacial course. Between the above-mentioned ledge on the east and the high hill on the west lies

FIG. 4. — "THE NARROWS," NEAR SOUTH SHERBORN.
The river is flowing through a narrow gorge, the marshes in the foreground being overflowed.

another, wider but similar, gorge, which is occupied by the flood plain of the river.

On the western side of the valley a rock and till ridge runs from the northern end of Pine Hill, west of Farm Pond, southward to Baggistere Brook in Millis. Between this ridge and the granite hill south of South Sherborn station is a gap of half a mile, which might well have been occupied by a preglacial river, except for several indications to the contrary. In the very centre of the gap two prominent ledges of slate occur. Although their presence makes a preglacial

gorge here improbable, it does not make it impossible; so for absolute proof it was necessary to look elsewhere.

For three miles north of the narrow gorge east of the hill the valley is one of varying character, in which numerous ledges occur, sometimes close to the river. A mile northeast of Farm Pond, near Clark Rock, conglomerate ledges descend on both banks into the water. West of Pegan Hill felsite rises abruptly both on the east and west, forming a narrow U-shaped gorge. East of the bend at this point the line of high land is continuous. To the west, ledges of felsite extend almost continuously across South Street to Long Pond, and from there northward to within 400 feet of Eliot Street (Figure 5). Nowhere do they offer a gap wide enough for a preglacial river valley. The only break which could be seriously considered is 600 feet wide, lying between the most northern felsite outcrop and the melaphyre, which outcrops 200 feet north of Eliot Street. About midway between these ledges, however, is a well, said to be about 20 feet deep and to rest on solid rock. Between here and Natick ledges are almost continuous. Considering these proofs, and also that in preglacial time the bed of the river must have been over a hundred feet below its present level, I believe we have conclusive evidence that between Dover and Natick there was no gap of sufficient size to connect the Middle with the Lower Charles. This evidence is strengthened by the presence of numerous ledges in the vicinity of South Natick.

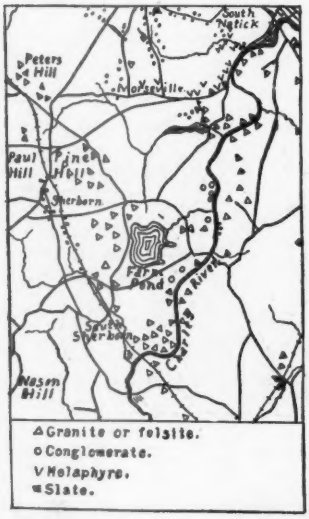


FIG. 5.—OUTCROP MAP OF A PORTION OF THE REGION BETWEEN MEDFIELD AND NATICK.

Nevertheless, the broad expanses of valley in the basin of the Middle Charles show that the region must necessarily have been traversed by streams of considerable size. As the outlets of these ancient streams cannot have been to the north, they must be searched for in some other direction. To find them, an analysis must be made of the valley of the Middle Charles.

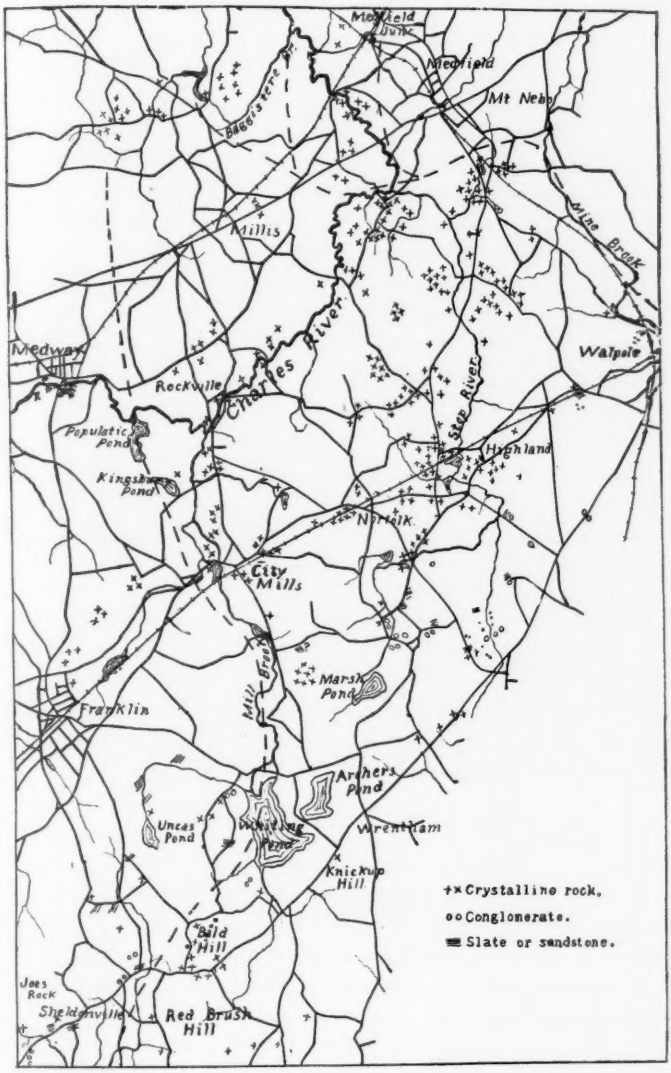


FIG. 6. — OUTCROP MAP OF A PORTION OF THE BASIN OF THE MIDDLE CHARLES AND VICINITY.

Flowing out of the narrow Medway gorge, the contrast is very great, as the river emerges into a broad, open valley, entirely devoid of outcrops, and with every characteristic of being very old. It flows in this valley for a mile and a half, as far as Green Street. Here, however, the characteristics suddenly change, and the direction becomes northeasterly for four miles, throughout which distance outcrops are occasional (Figure 6) and the topography rather characteristic of a distinctly postglacial stream. North of Forest Street an old valley is again encountered. In it the river turns eastward, as if to round the north side of Noon Hill; but instead, at the mouth of Stop River it turns towards the northwest. Stop River is a large tributary entering the Charles from the east, and at its mouth appears almost equal in size to the main stream. Its valley is certainly much broader, as shown by the contours. Between the 120-foot contours it is occupied by extensive meadows. Below its mouth, the valley of Stop River is continued with a width of from half a mile to a mile as far as Canal Street in Medfield, but interrupted near the Woonsocket Division of the New York, New Haven & Hartford Railroad by a series of outcrops (Figure 6). West of the railroad the broad valley is especially marked, as shown in Figure 7.

The topography shows that in the basin of the Middle Charles two portions are so broad and low that they must have been occupied by preglacial streams of considerable size. The first of these, lying between Medway and Rockville, I will call the Populatic River, from Populatic Pond. The other river, between Medfield and Millis, I will call the Baggistere, as it had its source in Baggistere Brook. The next problem is to determine the outlets of these preglacial streams from the basin.

By referring to Plate 1 it will be seen that the most prominent geological feature in this region is the band of Carboniferous sedimentary rocks forming the Norfolk County Basin, and stretching with a variable width of from one to three miles from the Narragansett Basin, at the northeast corner of Rhode Island, to the Boston Basin, north of the Blue Hills. This band of sedimentary rocks coincides to a considerable degree with a belt of lowlands, occupied on the northeast by the Neponset River and on the southwest by Abbots's Run.

At the beginning of the Glacial epoch sufficient time had elapsed since the origin of the streams of the region to enable them to become adjusted to the geological structure. Thus the streams originating

upon the crystalline areas to the northwest and southeast of the Norfolk Basin had come to take the most direct courses to the softer, sedimentary rocks. Of these streams the Populatic and the Baggistere were the most important.

The source of the Populatic River was in the western part of the town of Sherborn, at one of the sources of Baggistere Brook, with which it coincided as far as Orchard Street. It followed the broad, swampy valley south of Orchard Street as far as the present Charles.

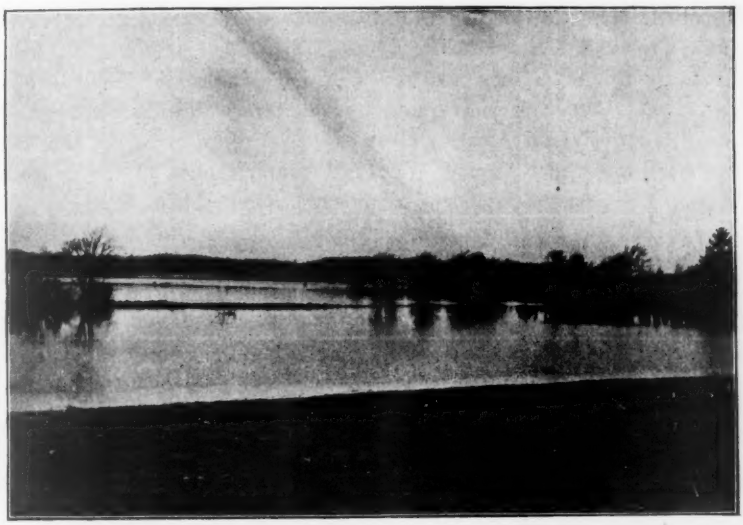


FIG. 7. — VALLEY OF CHARLES RIVER WEST OF THE WOONSOCKET DIVISION OF THE N. Y., N. H. & H. R. R., BETWEEN MEDFIELD AND MILLIS. MARSHES OVERFLOWED.

Farther south its course is marked by Populatic and Kingsbury ponds and Mill Brook, which it followed to the Norfolk Basin. Throughout almost the entire distance the bed-rock outcrops frequently along the western border of the valley, but it is exposed in the valley itself only near City Mills. Nowhere does it forbid regarding this as a preglacial course. Upon reaching the basin rocks the Populatic must have taken one of two courses. It may have turned northward to join the Neponset, or southward towards Abbots' Run. The latter course is the more probable. Nowhere between Marsh Pond and Walpole can evidences of a buried valley be found. But a southward sloping valley

between Whiting Pond and the gap west of Bald Hill in Wrentham would follow the narrow band of sedimentary rocks connecting the Norfolk and Narragansett basins. In the absence of any other plausible outlet for the Populatic River, we must accept this as its most probable location.

The Baggistere River was probably formed by the union of several brooks in the broad valley northwest of the Woonsocket Division, near the mouth of the present Baggistere Brook. The exact point of junction of the brooks must have been near the railroad in the vicinity of Island Street. Continuing the direction of the resultant of their courses towards the southeast, a broad, drift-filled valley is reached, extending to the marshy area south of Dwight Street. Near Causeway Street the river was joined by the brook flowing south from Castle Hill. East of here its most probable route is across the low watershed into the valley of Mine Brook, and thence to the Norfolk Basin. The probability of this is indicated by the broad, low valley of Mine Brook along the railroad between Medfield and Walpole. At first the great amount of rock east of Mt. Nebo seemed an obstacle to any preglacial course here. More careful examination, however, shows that most, if not all, of the rock between the railroad and Mt. Nebo is moraine material, and that the north-south ridge north of the railroad is a moraine separating the two valleys. An alternative course for the ancient river east of Causeway Street is through the valley of Stop River east of Noon Hill. This valley is less direct, however. Whichever course the river took, it joined the Neponset in the vicinity of Walpole, and was tributary to Boston Bay.

To summarize briefly, the basin of the Middle Charles was, in preglacial time, drained by two main streams, the Populatic and the Baggistere, both rising in Sherborn and flowing very directly to the Norfolk Basin. The Populatic reached the basin rocks north of Wrentham, then found an outlet to the Narragansett Basin, and thence to the sea through Miller's River and the Blackstone. Baggistere River, on the other hand, entered the Neponset Valley, which it followed to the sea through the Norfolk and Boston basins.

The Lower Charles. — We have seen that at the beginning of the Glacial epoch no part of the drainage south of Dover and Sherborn was tributary to the region on the north. Still, the broad valleys at several points below South Natick indicate that they must have been occupied by streams of considerable size.

South of the village of South Natick many prominent outcrops border the river and many occur even in its bed. Most of the higher lands both west and south of South Natick consist of solid rock. And this notwithstanding the fact that a long arm of the sedimentary and volcanic rocks of the Boston Basin extends as far west as Farm Pond (Plate I and Figure 5). At South Natick the outcrops extend across nearly the entire breadth of this belt, indicating that in preglacial time there was no large stream flowing into the Boston Basin through this area.

Below South Natick, following the river, we pass from a region of frequent outcrops to one where they are very scattering, and once more reach a portion of the valley which is undoubtedly very old. Between the ledge of melaphyre just below the dam at South Natick and the ledges near the corner of Dover and Grove streets, Wellesley, no outcrops occur, with the possible exception of a conglomerate exposure, perhaps a bowlder, on the Hunnewell estate. The outcrops in Wellesley and Needham are shown in Figure 8. The broad valley east of South Natick expands in two directions, extending far up the valley of Trout Brook, and also across Lake Waban and Morse's Pond, towards Cochituate. It probably also extends northward beneath the drift deposits of Wellesley and Needham. The sand-plains of this region rise to an extreme elevation of about 160 feet, in places rising steeply from the river in postglacial erosion slopes. Usually, however, the slopes are gradual, due to construction, and having been little eroded by the river. Near the mouth of Trout Brook the valley is very broad, but narrows down towards Charles River Village. Between Central Avenue and South Street outcrops are thick all along the river. The tortuous course between the ledges shows it at once to be of postglacial origin.

At South Street is a dam 8 feet in height, and below this outcrops occur on both banks, as shown in Figure 8. Just west of Chestnut Street ledges approach very near the river on both north and south, showing a strong probability that this was not a preglacial course. This is conclusively proved east of Chestnut Street, where a line of ledges crossing the river extends, both on the north and south, far back from the stream, offering no gap wide enough to contain a buried valley. The impossibility becomes still more evident when we consider that the bed of the preglacial stream must have been at least 100 feet below the present channel, as will be shown later. Between

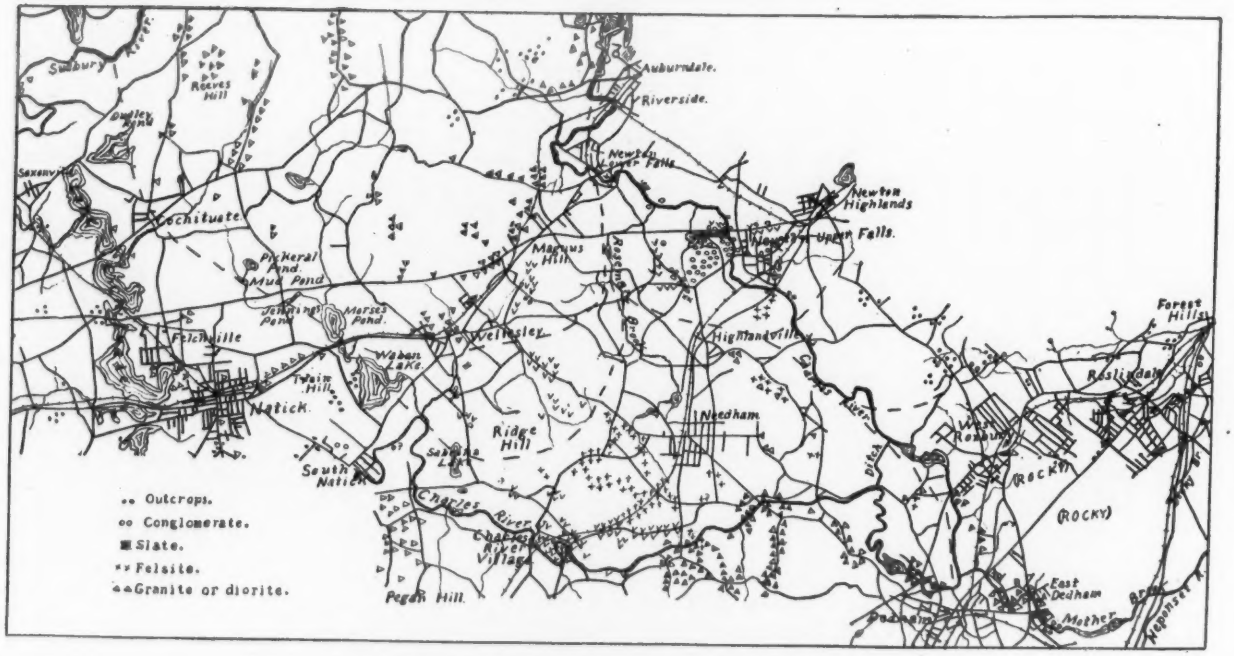


FIG. 8. — OUTCROP MAP OF A PORTION OF THE BASIN OF THE LOWER CHARLES.

Chestnut Street and Greendale Avenue the abundant outcrops near the river strengthen the proof that this part of the course is of post-glacial origin.

In the vicinity of Greendale Avenue the entire character of the valley changes, and the Charles emerges into a broad meadow, extending to the north for over two miles. Instead of following this direct course, the inconsistent river turns suddenly to the south towards the narrower end of the valley, and, reaching its termination west of Dedham Village, is forced to find a passage between the granite ledges which border it as far as Ames Street. At this point a broad, marshy

FIG. 9. — CHARLES RIVER MEADOWS ABOVE NAHANTON STREET, BETWEEN NEWTON AND NEEDHAM. (HIGH WATER.)

valley is again encountered, and turning at an acute angle, the river flows off to the northward. Half a mile below Ames Street an artificial ditch has been cut through the low divide on the east, diverting part of the water of the Charles into the rocky valley of Mother Brook leading to the Neponset, and thus making Boston an island. North of this the Charles flows sluggishly through broad marshes, which unite, west of Cow Island, with the marsh already noted, east of Greendale Avenue. This portion of the valley is clearly very old (Figure 9). But at Nahanton Street a ledge of melaphyre rises east of the river, and northeast of here the valley rapidly narrows. At Highland Avenue conglomerate occurs close to both banks; and south of High-

land Avenue and a quarter of a mile from the river a bold hill of felsite rises to an elevation of about 170 feet.

Below Central Avenue there is a sheer fall of 13 feet, and the river enters the picturesque Hemlock Gorge, and flows through it between steep ledges of conglomerate, which rise precipitously from the water. Figure 10 shows the distinctly postglacial character of the gorge. Below Worcester Street is a second dam, with a fall of 15 feet,

FIG. 10. — VIEW IN HEMLOCK GORGE, SHOWING THE UPPER FALL.

making the total height of Newton Upper Falls about 28 feet. Passing out of the gorge below Worcester Street, the stream again reaches a broad, low valley, through which it flows westward until, just below the mouth of Rosemary Brook, it strikes a ledge of conglomerate and turns slightly to the north. Beyond this point high sand-plains close in; and at Newton Lower Falls the valley has become very narrow, having without doubt been eroded by the river, as is indeed indicated by excavations in the steep slopes of the sand-plain. Enough sand has been removed so that the horizontal strata are seen to be cut off abruptly by the erosion slopes. In the bottom of the valley

at this point ledges of melaphyre occur, extending entirely across the river, and, together with artificial damming, making falls the total height of which is about 22 feet (Figure 11). Below Newton Lower Falls the river passes on to a band of soft rocks, and once more finds itself in a broad valley devoid of outcrops. A mile west of the falls it strikes the crystalline border of the Boston Basin, and is turned to the northeast towards Riverside. Between Riverside and Waltham

FIG. 11. — UPPER PORTION OF NEWTON LOWER FALLS.

outcrops are abundant on the west bank, occurring at Prospect Street, close to the water. On the east side of the river, the only ledges north of the Boston & Albany Railroad are several exposures of slate west of Auburndale. Below Waltham no outcrops occur near the river, except a ledge 100 feet south of the Bemis dam, and below this the nearest are 1,000 feet from the river, in Newton, opposite Watertown. Between Riverside and Cambridge there is no indication that the river is at any point far from its preglacial course.

This brief survey of the topography of the valley of the Lower Charles seems to warrant the following conclusions: —

1. That above South Natick there could have been no preglacial stream larger than a mere brook.

2. That in the regions between South Natick and Charles River Village, between Dedham and Newton Upper Falls, and between Newton Lower Falls and Riverside the valley is typically old.

3. That at both the Upper and Lower Falls, and between Charles River Village and Dedham, the Charles is certainly out of its preglacial course.

The explanation of these phenomena is found in evidence showing that the large basin between Dedham and Newton was formerly occupied by a separate stream, while the main river cut across Needham to its present valley below the Lower Falls.

It is probable, however, that the preglacial Charles did not have its principal source, as might be supposed, in the valleys of Natick and Dover; but that it rose far to the northwest. A peculiarity of the Sudbury River is the fact that, although in the upper part of its course it flows directly towards the Boston Basin to within five miles of its border, instead of taking the direct course of twenty miles to the sea across the softer basin rocks, it turns northward in the vicinity of Framingham to unite with the Assabet at Concord, forming the Concord River, which is tributary to the Merrimac at Lowell, and thence to the sea at Newburyport, making a total distance from Framingham of seventy-five miles. This course is evidently very unstable, and it must have been impossible for it to survive the complex stream adjustment which took place during the Tertiary period. The natural explanation is that between Concord and Saxonville the drainage has been reversed, and that in preglacial time the river had its source near Concord, flowing southward to the Charles through a valley now indicated in part by the basins of Morse's Pond and Lake Waban.

Outcrops occur on the east slope of Train Hill, opposite Wellesley College, and at Blossom Street, Wellesley; but between these points none have been found. Moreover, between the Sudbury west of Reeves' Hill and the Charles there is room for a buried valley over a mile wide, as shown by the absence of outcrops (Figure 8). A line drawn through Dudley, Pickerel, Jennings', and Morse's Ponds and Lake Waban, all kettle ponds, would mark approximately the most probable location of the buried valley. A convincing proof that such a valley lies beneath Wellesley is afforded by the record of a well

bored on the Mayo Farm, on Blossom Street, a mile north of the railroad. The well is located not far from the 160-foot contour, and went through 90 feet of sand and gravel without striking ledge. It must extend about 40 feet below the surface of Morse's Pond, and as it is apparently not in the direct line of the preglacial valley, it is extremely probable that the lowest line or axis of the gorge is at a much lower level. As further evidence that this was the course of the preglacial Sudbury River, it may be added that: —

1. The Sudbury River meadows are very narrow in the vicinity of Concord, but widen towards the south.

2. At several points near Concord outcrops occur near the Sudbury and Concord Rivers.

3. The tributaries of the Sudbury — Stows, Baiting, Wash, Hayward, and Cold Brooks — tend to converge toward the south rather than the north.

4. The portion of the Sudbury above and that below Cochituate converge toward this preglacial outlet.

The west branch of the Sudbury, flowing east from Westboro, must have combined with the north branch in the vicinity of Cochituate to form the Charles. It is probable that at that time the Assabet was tributary to the Sudbury through either Pantry or Hop Brooks. Thus the entire area now included in the Sudbury and Assabet basins drained into the Charles, which must, consequently, have been a stream of considerable size.

Upon reaching the Boston Basin the Charles probably turned northeastward and followed the basin rocks out to sea. An extended study has shown that between Wellesley and the Charles River east of Chestnut Street, Needham, outcrops are so thick that there are only two possible routes for the preglacial valley. One of these is eastward beneath Ridge Hill, and then northward between the felsite and melaphyre outcrops south of North Hill. The other, more direct and more probable, course is directly east from Lake Waban between the granite and sandstone outcrops, and beneath two large drumlins, to the valley of Rosemary Brook. The probability of the valley of this brook having once been occupied by the Charles is evident from its great size (Figure 12). It is out of all proportion to the size of the diminutive stream which now meanders through it; and north of Needham it is, for a width of a mile and a half, entirely free from outcrops almost to Newton Lower Falls.

The great size of this part of the ancient valley may have been due in part, however, to a stream flowing into it from the basin on the east. The principal tributaries to this basin were South Meadow, Palmer, and Wigwam Brooks, which united to form the broad valley along the western end of the West Roxbury slate belt. Evidence, aside from the surface topography, that a deep buried valley exists here is afforded by the records of numerous wells. At the Pumping Station of the Brookline Water Works, on the southwest point of Cow Island, a number of wells have been sunk to a depth of 90 feet below the surface. One of them strikes ledge at that depth. As the elevation of the surface at this point is about 93 feet, the wells evidently reach nearly to sea level. Beginning a mile northeast of this, and extending as far as Highland Avenue, numerous wells have been sunk for the Newton Water Works, the results of a few of which are given below.

WELLS ALONG THE PIPE LINE 25 TO 300 FEET SOUTH OF THE RIVER, BETWEEN STATION 0, 2,050 FEET NORTHWEST OF KENDRICK STREET, AND STATION 20 + 50, AT KENDRICK STREET.

STATION ON PIPE LINE.	ELEVATION OF BOTTOM OF WELL REFERRED TO SEA LEVEL. (In feet.)
Station 2 + 60	+ 43
Station 5 + 10	+ 20
Station 7 + 60	+ 13
Station 8 + 80	— 7
Station 9 + 30	— 34
Station 9 + 60	— 27
Station 9 + 80	— 35*
Station 10 + 20 to 10 + 50	— 20
Station 11 + 10 to 12 + 60	0 to + 10*
Station 12 + 10	— 35*
Station 16 + to 20 + 50	+ 50 to + 70
Station 20 + 50, 265 feet from river	+ 55

* Bed-rock not reached.

All the above wells reached bed rock at the depths given, except those at stations 9 + 80, 11 + 10 to 12 + 60, and 12 + 10, in which cases no rock was encountered. South of Kendrick Street and west

of the river the wells are all very shallow, no rock being reached in any case. Along the eastern side of the river another line of wells has been driven. The most westerly of these, some 2,000 feet south of Nahanton Street and 50 feet from the river, reaches bed-rock at an elevation of +16 feet. East of here the rock surface rises to + 36, 43, 47, and 57 feet in successive wells. The results of these borings show, first, that throughout this basin there is a deep buried valley extending east and west; and second, that about 1,000 feet north of Kendrick Street a buried gorge of great depth trenches the bottom

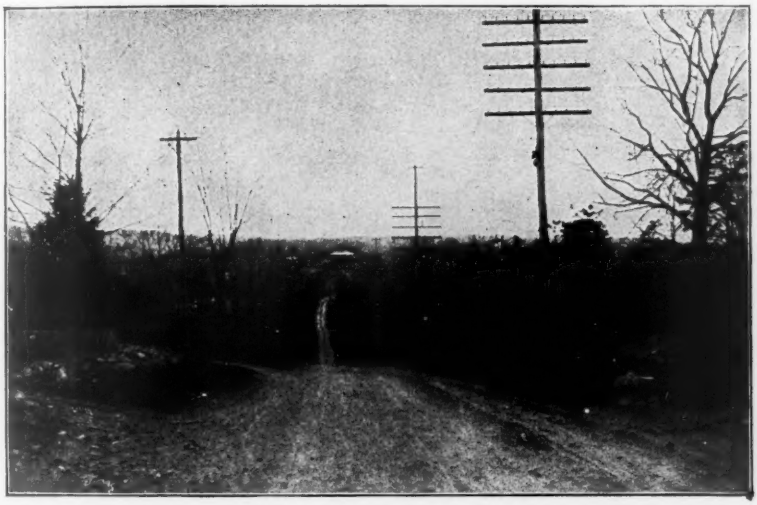


FIG. 12. — VALLEY OF ROSEMARY BROOK AT WEST STREET, WEST OF HIGHLANDVILLE.

of a north-south valley. This gorge, bounded as it is by outcrops on the east and west, must belong to a preglacial stream which was tributary to the east-west stream occupying the main valley, as described above. As the depth of the main valley must be at least as great as that of its tributaries, we must conclude that this, also, had a depth of *at least* 35 feet below sea level. And if this stream flowed westward into the Charles, the floor of that valley must have been still lower.

It has generally been supposed heretofore that the preglacial channel of the Charles around Newton Upper Falls diverged from the present river above Kendrick Street, passing south of the felsite

hill and through a narrow pass beneath the Sudbury Aqueduct just east of Cedar Street to the broad meadows in the vicinity of Worcester Street. A more direct and more probable course, however, is directly westward from Kendrick Street to the valley of Rosemary Brook west of Highlandville. Along this line there is a gap over a mile in width occupied by the sand-plain, having an elevation of from 120 to 140 feet, above which not an outcrop appears (Figure 8). In the gap at the aqueduct, on the other hand, the breadth of the bed-rock valley on the surface is certainly less than 600 feet, and probably less than half that. The lowest elevation of the surface is about 105 feet; but on both sides of this point, a few hundred feet distant, ledges rise to elevations up to 160 feet. Thus, although nothing has been found to absolutely disprove this route, we must accept the Highlandville course as the more probable of the two.

The only objections to a westward flowing stream here are that the course is retrograde, and that it passes from the slate belt to the harder felsite to the west; but this may be partly explained by assuming that formerly the slate was continuous westward to the valley of the Charles. A possible alternative course for the Charles would be to consider that, instead of turning north towards Waltham, it flowed eastward from Highlandville and followed the slate belt out to Boston Bay, across West Roxbury and Dorchester. I have considered this view, but have been able to find no direct evidence to sustain it. Moreover, at several points along the slate belt the gaps between the outcrops are so narrow as to render the course improbable. This is especially the case east of Franklin Field, Dorchester, where slate has been thrown out in excavating for sewers. For similar reasons, any attempt to trace a preglacial outlet through the valley of Stony Brook must be abandoned. An outlet along Mother Brook is impossible. Although this stream crosses the Neponset-Charles watershed at its lowest point, the channel is so tortuous and rocky that it cannot be considered for a moment.

We must, then, suppose that from near Highlandville the course of the preglacial Charles was northwest to the present river below Newton Lower Falls, and that from there on it had approximately its present location. The existence of a deep gorge below the present river at Waltham is shown by several wells in that vicinity. A well at the Waltham Bleachery was driven to a depth of 70 feet below and one at the American Watch Tool Company to 63 feet below sea level

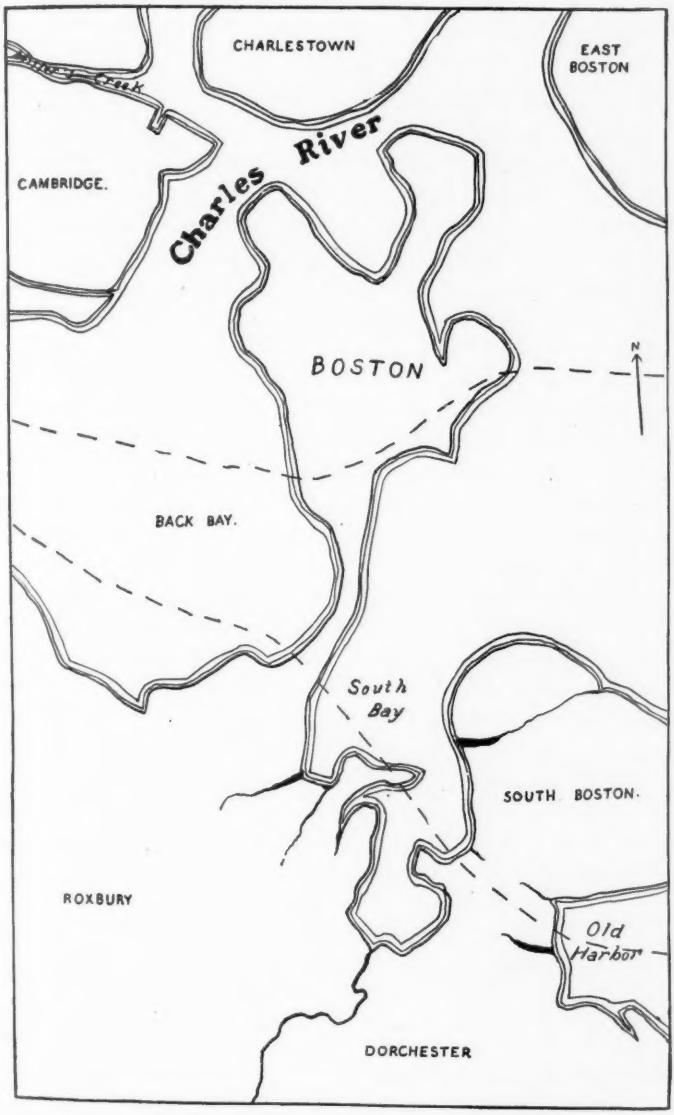


FIG. 13. — OUTLINE MAP OF BOSTON AS IT WAS BEFORE THE POSITION OF THE SHORE LINE WAS CHANGED BY ARTIFICIAL FILLING. (From an old map.)

without reaching bed-rock. And wells at the Waltham Gas Company and the Davis & Farnham Foundry Company reached ledge at depths of —40 and —62 feet, respectively.

The Tide Water Portion of the Charles. — The portion of the Charles southeast of Cambridge unquestionably overlies a preglacial valley. In planning for the construction of the Harvard and West Boston bridges many borings were made to depths varying between 30 and 80 feet, none of which reached bed-rock. Around the northwest side of Beacon Hill, however, according to Mr. W. W. Dodge,[1] rock rises to sea level and has been encountered in many excavations for sewers and cellars. In boring for the bridge of the Boston & Lowell Railroad, in 1833, rock was struck on the Boston side 12 feet below low water. These and many other similar facts make it probable that a continuous ridge of rock passes beneath the river north and northwest of Beacon Hill, presenting an effective barrier to an ancient channel on this side of Boston.

The true preglacial valley must, therefore, lie to the south of Beacon Hill. Until the latter part of the nineteenth century the city was connected with Roxbury only by a narrow neck of land along Washington Street, between Pleasant and Dartmouth streets (Figure 13). The land on either side of this neck, out to the present bank of the Charles on the west and to Fort Point Channel on the east, has all been formed by artificial filling. Dorchester Neck, between South Boston and Dorchester, is at present but half a mile across, and in the early days consisted of a marsh, which at times of very high tides was entirely covered, making South Boston an island. In the area between Beacon Hill and a line drawn from Roxbury Crossing to Mt. Vernon Street, Dorchester, there is not a single outcrop, with the exception of ledges in South Boston. The topography suggests at once that the early pleistocene course of the river was east or southeast from the Back Bay. And such a course is practically proved by numerous artesian wells, the data for a few of which follows.

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[1] Notes on the Geology of Eastern Massachusetts. Proc. Bos. Soc. Nat. Hist., Vol XXI, pp. 197–215.

IN BOSTON PROPER.

	Location.	Depth of bed-rock in feet.
1.	Post-Office Square	105 [1]
2.	Edison Electric Illuminating Co., Liverpool Wharf, Atlantic Avenue, opposite Pearl Street	83
3.	Federal Court — Federal Street	80
4.	Atlantic Avenue, corner Congress Street	90
5.	Boring for Congress Street Bridge	43.5
6.	Adams House, 553 Washington Street	120
7.	Near Old Elm, Boston Common	105 [1]
8.	Old Boston & Providence Railroad Station, Park Square	163
9.	Hotel Plaza, corner Columbus Avenue and Holbrook Street	99
10.	53 West Brookline Street, corner Washington	83
11.	Allen Gymnasium, corner St. Botolph and Garrison Streets	140 [1]
12.	791 Tremont Street, corner Northampton	170
13.	Corner Swett and Albany Streets	105 [1]

IN CAMBRIDGE.

14.	Near outlet of Fresh Pond	148
15.	Brigham's, Massachusetts Avenue, Cambridgeport	120
16.	Soap Works, corner Davis Street and Broadway, Cambridgeport	110–115
17.	John P. Squires & Co., Gore Street, East Cambridge	60

IN SOUTH BOSTON AND DORCHESTER.

18.	Pier 4, South Boston	118 [1]
19.	Just to south, on next pier	35
20.	Old Calf Pasture, Mt. Vernon Street	166

ON LINE OF SEWERAGE TUNNEL FROM CALF PASTURE TO SQUANTUM.

21.	West Shaft, Pumping Station	over 100
22.	Rock rises towards the east to about level of low water.	

23. North of Dorchester Street exists a ledge of slate, which was formerly quarried.
24. Dredgings in the harbor have struck rock in many places between Castle and Governor's Islands.
25. North of Governor's Island borings of 40 feet have failed to reach rock.

Comparing these data, it is seen from 14, 15, and 16 that beneath Cambridgeport the bed-rock is from 110 to 150 feet below sea level, but that it rises towards the north, as shown by 27, forming an east-west ridge extending as far east as Beacon Hill. In Post-Office Square the rock surface is again very low (1). South of Beacon Hill is an east-west gorge of great depth (6, 7, and 8), which probably passes eastward between Post-Office and Dewey Squares; and 25 indicates that the gorge may be extended eastward between Governor's Island and East Boston. South of Park Square the bed-rock

[1] Bed-rock not reached.

rises, as shown by 9 and 10, to between 80 and 100 feet below sea level, forming a ridge which is shown by numerous outcrops in South Boston and Boston Harbor to be continued as far east as Castle Island (23 and 24). South of this ridge is a second deep gorge. The lowest rock surface shown by the records is at 791 Tremont Street, near Northampton (12), where it is nearly 170 feet below sea level.[1] Borings 13, 20, and 21 show this gorge to be extended east between South Boston and Dorchester to the Old Harbor.

Thus the preglacial gorge of the Charles beneath Boston must have one of two locations. The course most in line with the river to the west would be the more northern one. But the bend which would be necessary in that case between the outcrops west of Beacon Hill and the comparatively shallow borings near Dewey Square is an unnatural one. A straighter course, and one giving room for a wider gorge, is the southern one, which is also the one in which the lowest bed-rock surface has been found (12, 20).

Moreover, the deep borings in Cambridge are exactly in line with the southern gorge, and the topographical map shows that, with a slight bend to the north, the surface depression here continues with an average width of two miles across Belmont and Arlington to the Mystic Lakes at West Medford. Professor Crosby has shown[2] that the Merrimac River in preglacial time was probably tributary to Boston Bay. If such was the case, its most direct course would be southward from Arlington along this depression to the Old Harbor. Hence the preglacial Charles was a branch of the Merrimac, meeting it in the vicinity of Cambridgeport. An alternative course for the Merrimac is eastward from West Medford through the valley of the Mystic; but as this would necessitate a sharp bend at West Medford, I consider it less probable.

As the Pleistocene elevation of the land carried the shore line in the vicinity of Boston much farther east than it is at present, the streams of that time had to cut their gorges in rock which is now deeply buried beneath the bay. Two courses must be considered for the Charles (or the Merrimac) after reaching the Old Harbor: a northern one, passing just south of Castle Island, and thence north-

[1] As the elevation of the land between Beacon Hill and Roxbury is but a few feet above high water, it may practically be neglected here.

[2] Geological History of the Nashua Valley, *l. c.*, p. 302.

east; and a southern one, towards Thompson's and Moon Islands and Nantasket. Between Nash's Rocks, north of Point Allerton, and Moffit's Ledge, over two miles farther north, ledges are so frequent as to afford no probable location for a valley. This band of ledges, trending approximately northeast and forming the Outer Islands, is a continuation of the line of outcrops in the lower Neponset Valley, and exposed in Squantum, on Moon Island, and in Sculpin Ledge. It is improbable that this ridge was crossed by the preglacial channels of either the Neponset or the Charles, but it more likely formed a divide between them. Moreover, northeast of the Calf Pasture extends a broad, open area, unobstructed by any land, except Deer Island, which is a drumlin; and this is regarded as the most probable course of the submarine gorge of the preglacial Charles.

[To be concluded in the next number of the QUARTERLY.]

RESULTS OF TESTS MADE IN THE ENGINEERING LABORATORIES.

XIII.

Steam, Hydraulics, and Applied Mechanics.

Measurement of Air with an Orifice.

The increasing use of compressed air as a motive power makes desirable some simple method of determining the quantity of air consumed. At present we have only Fliegner's formulæ, based upon his experiments with two small orifices, 4.085 mm. and 7.314 mm. in diameter and with pressures under five atmospheres.

To test the availability of these formulæ for larger orifices and higher pressures, and if necessary to establish new formulæ, the apparatus shown in the accompanying cut (Figure 1) has recently been installed in the Mechanical Engineering Laboratory.

The battery of twelve tubes, tested to stand hydraulic pressure of 3,500 pounds per square inch, is piped to form three units of two and two units of three tubes each, thus permitting the use of any number at once. Because of the difficulty in preventing leakage through the connecting valves, it has been found advisable in practice to use the entire reservoir. The slight leakage about the stuffing boxes can be so minimized as to be negligible. These supply tubes are connected by piping to a large receiver, the admission of the air being controlled by a throttle valve placed in this pipe. The receiver has a safety valve set at about 350 pounds, so this determines the maximum pressure that can be used with the present arrangement.

The orifices are all made with the length of the cylindrical part one and one-half times the diameter and with a radius of the rounded approach equal to the diameter. The orifices were carefully made by a

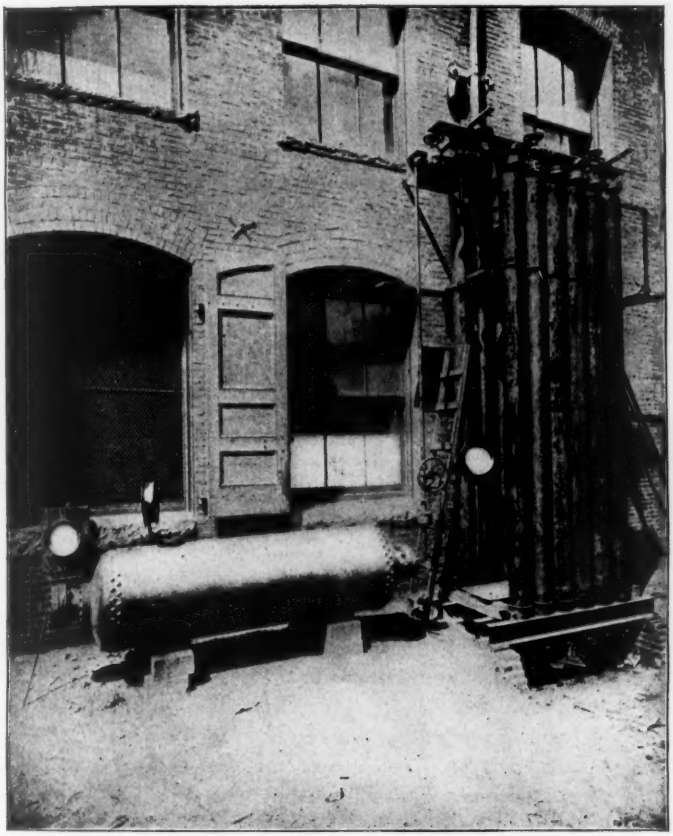

FIG. 1. — APPARATUS FOR THE MEASUREMENT OF AIR WITH AN ORIFICE.

skilled workman, care being taken to avoid any scratches which might affect the passage of air. When finished the diameter of each was carefully determined by fitting an arbor of slight taper into the hole and calipering the arbor with a micrometer caliper. At the centre of the straight cylindrical part of the orifice is a hole $\frac{1}{64}$-inch in diameter, drilled at right angles to the axis of the orifice and connected by piping to a pressure gauge.

The reservoir and receiver were fitted with gauges and thermometers. These instruments were carefully calibrated and the corrections applied to all the readings. The volume of the receiver and each of the twelve tubes was obtained by weighing the amount of water of known density necessary to fill them, and that of the piping was calculated from careful measurements. The total volume of the twelve tubes and the piping down to the throttle valve is 49.11 cubic feet (V_t), and of the receiver and piping from the throttle valve is 41.14 cubic feet (V_R).

To make an experiment the orifice was first closed with a wooden plug held against it by means of a lever, and then the pressure and temperature of the air in both the receiver and the tubes forming the reservoir were recorded. Air was next admitted to the receiver until the desired pressure had been obtained, when the orifice was uncovered and a stop watch was started simultaneously. Readings were then taken, at half-minute intervals, of the pressure in the orifice and of the pressure and temperature in the receiver. At the close of the test, produced by closing the throttle valve, the watch was stopped, and at the same time final readings were taken of the pressure and temperature in the receiver. During the test the pressure was kept nearly constant by regulating the throttle valve, but the temperature in the receiver would rise rapidly at first and then gradually fall again as colder air came in from the reservoir. At the close, after the temperature in the supply tubes had become constant, a final reading was taken of the pressure and temperature. As it takes some two or three hours to fill the tubes to a pressure of 2,500 pounds to the square inch, and only about 3 minutes to empty them with a $\frac{5}{8}$-inch orifice, it was found advantageous to save as much of the air as possible; so at the end of some of the tests the plug was replaced before all the air had escaped from the receiver. This accounts for the initial pressure (P_0) so often being different from atmospheric pressure.

The air was supplied by a three-stage Norwalk Air Compressor, and contained from day to day varying amounts of moisture and also of cylinder oil. It was assumed, in working up the results, that the air followed the law of perfect gases up to 200 pounds pressure on the square inch, and that above 200 pounds it follows the same deviation as the dry air experimented upon by E. H. Amagat. Interpolating the pressures in Amagat's results gave the specific volumes (V_1, V_2) at 32° F. From these and the observed temperatures were obtained the densities of the air in the reservoir before and after the test (w_1 and w_2, respectively), and also in the receiver before starting and at the moment the throttle valve was closed (w_0 and w_3, respectively).

The weight of air that has passed the orifice is equal to that which has left the tubes minus the increase of weight in the receiver, or the weight per second is

$$G = \frac{1}{S}\left[V_t (w_1 - w_2) - V_R (w_3 - w_0)\right]$$

where

G = pounds of air passing orifice per second.
S = duration of test in seconds.
V_t = volume of reservoir = 49.11 cubic feet.
V_R = volume of receiver = 41.14 cubic feet.
w_1 = weight of 1 cubic foot of air in tubes at start.
w_2 = weight of 1 cubic foot of air in tubes at close.
w_3 = weight of 1 cubic foot of air in receiver at close.
w_0 = weight of 1 cubic foot of air in receiver at start.

In the accompanying tables the tests given by date were made by the Seniors as part of the regular laboratory exercises; those designated by numbers are taken from the thesis of Messrs. Putnam and Sweetser. Although the observations are not sufficiently numerous to justify the final establishment of new equations, they still permit of one or two interesting deductions.

When the pressure in the receiver was more than twice the atmospheric pressure, a condition fulfilled in all these tests, Fliegner found that the pressure in the orifice was always the same propor-

tionate part of the pressure in the receiver. The present observations not only bear out this statement, but seem to show that there is a different ratio for each orifice.

If the results are plotted with the average receiver pressure (P_3 average) as abscissæ and pounds of air per second (G) as ordinates, it is possible to give a close approximation to the results by a series of straight lines, one for each orifice, converging at the origin. A general expression for the results is, then, of the form $G = C.P.$ (1). The thermodynamic equation for the adiabatic flow of air through an orifice is

$$G = A\sqrt{\frac{2g}{R}}\ \frac{\kappa}{\kappa-1}\left[\left(\frac{P_4}{P_3}\right)^{\frac{2}{\kappa}} - \left(\frac{P_4}{P_3}\right)^{\frac{\kappa+1}{\kappa}}\right]^{\frac{1}{2}}\frac{P_3}{\sqrt{T_3}}.$$

A = area of orifice in square inches.
κ = 1.405 the ratio of the specific heats.
R = 53.22.
T = absolute temperature.
P = absolute pressure per square inch.

The above equation can be made to represent the flow where the expansion is not quite adiabatic nor frictionless, as shown by Zeuner, by writing it in the form

$$G = A\sqrt{\frac{2g}{R}}\cdot\frac{\kappa}{\kappa-1}\left[\left(\frac{P_4}{P_3}\right)^{\frac{2}{n}} - \left(\frac{P_4}{P_3}\right)^{\frac{n+1}{n}}\right]^{\frac{1}{2}}\frac{P_3}{\sqrt{T_3}} \quad \ldots\ (2)$$

where $n < \kappa$ and to be determined by experiment. Equation (2) has the form

$$G = \frac{\text{area} \times k_a}{\sqrt{T_3}}\ P_3 \quad \ldots\ (3)$$

By comparing equations (3) and (1), it is evident that the constant (C) embraces the area of the orifice, the temperature at which the experiments were made and a certain constant (k_a) dependent upon the size of the orifice.

As all the results may thus be represented by equation (3), it would be easier to determine the value of (k_a) from a plot if the effect

of the varying temperature were eliminated. The value of (G) has, therefore, been corrected to 32° F. by means of the equation

$$G_0 = G \frac{\sqrt{T_3 \text{ average}}}{\sqrt{492.7}}$$

It is hoped in the near future that enough data will be collected on different orifices to finally establish the values of the constants in the above equations.

FLOW OF AIR THROUGH AN ORIFICE.

Diameter of orifice, 0.1890 inch.

No. or date of test.	Barometer.	Initial pressure in receiver. (Abs.)	Initial temperature in receiver. (Abs.)	Initial pressure in reservoir. (Abs.)	Initial temperature in reservoir. (Abs.)	Final pressure in reservoir. (Abs.)	Final temperature in reservoir. (Abs.)	Final pressure in receiver. (Abs.)	Final temperature in receiver. (Abs.)	Average pressure in receiver. (Abs.)	Average temperature in receiver. (Abs.)	Average pressure in orifice. (Abs.)	Duration of test in seconds.
		P_0.	T_0.	P_1.	T_1.	P_2.	T_2.	P_3 final	T_3 final.	P_3 average.	T_3 average.	P_4.	
Mar. 12	14.49	14.49	501.6	255.5	498.5	140.5	497.6	54.3	503.9	53.4	507.8	31.3	596.4
Mar. 15	14.61	14.61	499.2	545.6	495.8	355.6	493.2	80.7	499.9	80.6	506.5	48.3	570.0
Mar. 14	14.64	14.64	495.2	447.6	495.6	223.6	495.9	95.0	497.7	94.8	500.1	57.2	660.0
Mar. 12	14.47	14.47	509 3	507.5	503.5	211.5	499.4	123.4	507.1	123.5	514.8	72.7	656.0
Mar. 15	14.61	14.61	496.3	805.6	493.2	524.6	489.5	131.1	497.0	129.6	505.5	76.9	600.0
No. 1	14.93	37.5	499.7	592.9	503.0	533.9	503.5	38.0	504.2	39 2	503.1	23.0	599.75
No. 2	14.93	63.2	501.7	682.9	502.1	592.9	503.0	66.4	505.7	64.6	504.2	37.7	601.75
No. 3	14.93	77.0	521.0	822.9	503.5	682.9	501.1	88.2	507.1	89.3	512.7	52.0	599.75
No. 4	14.75	117.8	502.1	451.7	505.8	289.7	502.6	113.3	505.5	113.7	504.6	65.5	600.25
No. 5	14.76	136.3	505.5	1672.	506.9	1453.	505 8	141.5	504.8	139 4	506.0	80.1	599.5
No. 6	14.76	141.4	509.3	1978.	512.7	1672.	506.9	165.7	505.7	163.6	509.4	93.0	600.0
No. 7	14.76	14.76	512.9	2509.	521.7	1966.	510.7	189 3	508.9	189.2	520.4	107.5	600.25
No. 8	14.75	183.1	503.5	790.7	508.7	449.7	501.5	213.7	507.5	214.0	509.1	122.1	602.0
No. 9	14.75	173.8	508.0	1217.	515.0	781.7	505.5	239.3	508.0	239.2	512.5	136 4	600.5
No. 10	14.75	14.75	504.9	2310.	513.6	1639.	500.3	263.7	502.4	264.4	514.3	156.8	599.75
No. 11	14.75	14.75	511.8	1403.	512.3	830.7	500.8	287.9	508 2	288.7	516.8	164.1	600.25
No. 12	14.75	14.75	514.5	2219.	523.1	1395.	508.4	313.7	509.4	315.6	521.9	179.6	600.5

FLOW OF AIR THROUGH AN ORIFICE.

Diameter of orifice, 0.1890 inch. — *Concluded.*

No. or date of test.	Weight of 1 cu. ft. of air under conditions P_0 and T_0.	Specific volume of air under conditions P_1 and 32° F.	Weight of 1 cu. ft. of air under conditions P_1 and T_1.	Specific volume of air under conditions P_2 and 32° F.	Weight of 1 cu. ft. of air under conditions P_2 and T_2.	Weight of 1 cu. ft. of air under conditions P_3 and T_3.	Lbs. of air through orifice per second, under conditions P_2 average, and T_3 average.	Lbs. of air through orifice per second, under conditions P_3 average, and 32° F.	Ratio of pressure in orifice to pressure in receiver.
	w_0.	v_1.	w_1.	v_2.	w_2.	w_3.	G.	G_0.	$P_4 \div P_3$.
Mar. 12	.0782	.6941	1.424	....	0.8183	.2915	.03525	.03578	.5863
Mar. 15	.0792	.3290	3.021	.5060	1.974	4369	.06445	.06534	.5991
Mar. 14	.0800	.4030	2.485	.7966	1.247	.5164	.06501	.06549	.6037
Mar. 12	.0771	.3543	3.317	.8477	1.164	.6584	.08329	.08513	.5888
Mar. 15	.0797	.2219	4.492	.3436	2.929	.7137	.08457	.08561	.5937
No. 1	.....	.....	.....	....	.....	....	.0270	.0273	.5867
No. 2	.....	.....	.....	....	.....	....	.0396	.0401	.5836
No. 3	.....	.....	.....	....	.....	....	.0582	.0594	.5822
No. 4	.....	.....	.....	....	.....	....	.0711	.0719	.5760
No. 5	.....	.....	.....	....	.....	....	.0994	.1007	.5745
No. 6	.....	.....	.....	....	.....	....	.118	.120	.5685
No. 7	.....	.....	.....	....	.....	....	.138	.142	.5682
No. 8	.....	.....	.....	....	.....	....	.137	.139	.5692
No. 9	.....	.....	.....	....	.....	....	.158	.161	.5702
No. 10	.....	.....	.....	....	.....	....	.164	.167	.5929
No. 11	.....	.....	.....	....	.....	....	.187	.191	.5685
No. 12	.....	.....	.....	....	.....	....	.227	.234	.5691

FLOW OF AIR THROUGH AN ORIFICE.

Diameter of orifice, 0.2515 inch.

No. or date of test.	Barometer.	Initial pressure in receiver. (Abs.)	Initial temperature in receiver. (Abs.)	Initial pressure in reservoir. (Abs.)	Initial temperature in reservoir. (Abs.)	Final pressure in reservoir. (Abs.)	Final temperature in reservoir. (Abs.)	Final pressure in receiver. (Abs.)	Final temperature in receiver. (Abs.)	Average pressure in receiver. (Abs.)	Average temperature in receiver. (Abs.)	Average pressure in orifice. (Abs.)	Duration of test in seconds.
		P_0.	T_0.	P_1.	T_1.	P_2.	T_2.	P_3 final.	T_3 final.	P_3 average.	T_3 average.	P_4.	
Feb. 28	14.78	14.78	496.7	713.8	497.6	564.8	493.6	48.7	494.1	48.9	499.1	25.0	600.0
Feb. 25	14.69	14.69	495.2	469.7	499.9	281.7	499.9	53.6	496 7	53.6	500 7	27.9	705.0
Mar. 4	14.67	14.67	501.7	739.7	501.7	552.7	501.7	54.5	501.0	53.8	505.9	28.0	660.0
Feb. 28	14.78	14.78	496.7	554.8	487.1	355.8	483.9	62.9	489.5	63.0	495.8	33.0	600.0
Mar. 5	14.51	14.51	509.4	1346.5	509.4	1139.5	497.2	65.4	496.1	64.4	502.1	33.9	600.0
Mar. 1	14.76	14.76	506.4	1229.	506.2	844.8	500.3	113.3	499.7	113.2	508.5	59.6	600.0
Feb. 26	14.60	14.60	505.1	1068.	505.1	672.6	503.5	113.0	499.7	113.2	508.7	59.2	623.4
Mar. 5	14.46	14.46	497.9	1150.	496.3	756.4	495.4	112.3	499.2	113.3	505.3	59.6	600.0
Feb. 26	14.47	14.47	504.8	669.5	504.8	161.5	505.1	164 4	507.5	167.1	519.1	88.7	525.0
No. 13	14 72	35.5	496.7	324.7	500.3	228.7	501.7	37.8	504.2	37.7	501.2	19.4	599.75
No. 14	14.72	60.7	494.9	489.7	503.1	324.7	500.3	62.9	503.5	63.0	501.7	31.6	600.25
No. 15	14.84	81.2	535.4	260.8	514.5	103.8	511.8	86 6	525.6	87.0	530.0	43.4	393.75
No. 16	14.58	14.58	506.4	1014.6	506.6	624.6	499.0	114.1	504.8	113 5	512.1	56.9	600.0
No. 17	14.72	160.7	497.4	922.7	499.7	479.7	495.4	164.0	502.4	164.7	501.9	79.4	600.0
No. 18	14.73	88.5	494.3	929 7	500.8	332.7	491.6	188.2	499.9	189 0	504 0	96.1	600.0
No. 19	14.73	14.73	495.0	945.7	509.4	211.7	495.0	208.2	511.1	213 6	523.1	109.1	602.25
No. 20	14.72	14.72	507.1	1783.	518.6	922.7	499.7	263.7	504.6	264.5	517.3	126.3	600 0
No. 21	14.73	14.73	512.7	1985.	514.5	919 7	493 8	288.7	498.6	289 8	513.0	147.0	600.5
No. 22	14.76	14.76	510.7	1472.	509.6	385 8	507.3	313 8	505.3	314.1	517.5	159.6	600.0

FLOW OF AIR THROUGH AN ORIFICE.

Diameter of orifice, 0.2515 inch. — *Concluded.*

No. or date of test.	Weight of 1 cu. ft. of air under conditions P_0 and T_0	Specific volume of air under conditions P_1 and 32° F.	Weight of 1 cu. ft. of air under conditions P_1 and T_1.	Specific volume of air under conditions P_2 and 32° F.	Weight of 1 cu. ft. of air under conditions P_2 and T_2.	Weight of 1 cu. ft. of air under conditions P_3 and T_3.	Lbs. of air through orifice per second, under conditions P_3 average, and T_3 average.	Lbs. of air through orifice per second, under conditions P_3 average, and 32° F.	Ratio of pressure in orifice to pressure in receiver.
	w_0.	v_1.	w_1.	v_2.	w_2.	w_3.	G.	G_0.	$P_4 \div P_3$.
Feb. 28	.0805	.2513	3.923	.3178	3.141	.2667	.05297	.05331	.5122
Feb. 25	.0803	.3835	2.570	.6314	1.086	.2920	.05800	.05847	.5205
Mar. 4	.0791	.2423	4.053	.3247	3.025	.2944	.06315	.06399	.5204
Feb. 28	.0805	.3235	3.127	.5057	2.013	.3477	.07298	.07320	.5238
Mar. 5	.0771	.1325	7.300	.1564	6.337	.3567	.05973	.06030	.5264
Mar. 1	.0789	.1453	6.622	.2116	4.655	.6135	.1245	.1265	.5265
Feb. 26	.0782	.1668	5.848	.2667	3.669	.6119	.1365	.1387	.5318
Mar. 5	.0786	.1548	6.414	.2368	4.200	.6087	.1450	.1469	.5260
Feb. 26	.0776	.2679	3.643	1.1280	0.8648	.8766	.1975	.2027	.5308
No. 13	.....	.....	.....	.....	.....	.....	.0422	.0426	.5591
No. 14	.....	.....	.....	.....	.....	.....	.0715	.0721	.5016
No. 15	.....	.....	.....	.....	.....	.....	.116	.120	.4989
No. 16	.....	.....	.....	.....	.....	.....	.134	.137	.5013
No. 17	.....	.....	.....	.....	.....	.....	.199	.201	.4821
No. 18	.....	.....	.....	.....	.....	.....	.230	.233	.5085
No. 19	.....	.....	.....	.....	.....	.....	.250	.258	.5108
No. 20	.....	.....	.....	.....	.....	.....	.275	.282	.4775
No. 21	.....	.....	.....	.....	.....	.....	.345	.352	.5072
No. 22	.....	.....	.....	.....	.....	.....	.375	.384	.5081

FLOW OF AIR THROUGH AN ORIFICE. Diameter of orifice = 0.3753 inch.

Number.	Barometer. (Lbs. per square inch.)	Initial pressure in receiver. (Abs.) $P_{6'}$	Initial temperature in receiver. (Abs.) $T_{6'}$	Initial pressure in reservoir. (Abs.) $P_{1'}$	Initial temperature in reservoir. (Abs.) $T_{1'}$	Final pressure in reservoir. (Abs.) $P_{2'}$	Final temperature in reservoir. (Abs.) $T_{2'}$	Final pressure in receiver. (Abs.) P_8 final.	Final temperature in receiver. (Abs.) T_8 final.	Average pressure in receiver. (Abs.) P_8 average.	Average temperature in receiver. (Abs.) T_8 average.	Average pressure in orifice. (Abs.) $P_{4'}$	Duration of test in seconds.	Lbs. of air through orifice per second, under conditions P_3 average, and T_3 average. $G.$	Lbs. of air through orifice per second under conditions P_3 average and 32° F. $G_{0'}$	Ratio of pressure in orifice to pressure in receiver. $P_4 \div P_3$.
23	14.93	37.3	499.7	996.9	499.9	871.9	499.0	38.0	501.5	38.5	501.9	19.6	299.75	.113	.114	.5091
24	14.93	59.2	501.3	1165.9	498.5	980.9	496.3	63.1	501.3	63.5	503.0	31.1	300.0	.162	.164	.4898
25	14.93	88.4	502.8	1434.9	500 8	1159 9	496.1	88 4	500.4	88.8	502 2	42.8	300.0	.240	.242	.4819
26	14.82	98.7	515.9	624.8	499.5	287.8	491.8	112.1	504.0	112.8	509.4	55 8	300.5	.285	.290	.4948
27	14.93	142.7	532.8	1991.9	506.7	1404.9	495.6	165.0	502.4	165.0	513.8	77.5	300.75	.403	.473	.4697
28	14.82	178.5	539.2	1607.8	510.5	664.9	489.3	213.9	500.6	214.7	509.8	105.2	420.25	.565	.575	.4900
29	14.84	92.2	513.2	999.8	514.8	302.9	494.7	255.8	521.3	263.2	533.4	123.9	212.5	.678	.706	.4707
30	14.84	14.8	530.3	2284.8	528.5	977.8	501.3	313.8	517.7	313.9	534.5	147.3	299.5	.850	.885	.4693

FLOW OF AIR THROUGH AN ORIFICE. Diameter of orifice = 0.4993 inch.

Number.	Barometer. (Lbs. per square inch.)	Initial pressure in receiver. (Abs.) P_0.	Initial temperature in receiver. (Abs.) T_0.	Initial pressure in reservoir. (Abs.) P_1.	Initial temperature in reservoir. (Abs.) T_1.	Final pressure in reservoir. (Abs.) P_2.	Final temperature in reservoir. (Abs.) T_2.	Final pressure in receiver. (Abs.) P_3 final.	Final temperature in receiver. (Abs.) T_3 final.	Average pressure in receiver. (Abs.) P_3 average.	Average temperature in receiver. (Abs.) T_3 average.	Average pressure in orifice. (Abs.) P_4.	Duration of test in seconds.	Lbs. of air through orifice per second, under conditions P_3 T_3 average. G.	Lbs. of air through orifice per second, under conditions P_3 average, and 32° F. G_{32}.	Ratio of pressure in orifice to pressure in receiver. $P_4 \div P_3$.
31	14.69	34.8	496.3	525.7	496.1	328.7	492.7	37.8	499.9	37.8	499.7	19.9	299.75	.173	.174	.5265
32	14.69	59.5	502.4	851.7	498.5	515.7	490.7	62.9	498.6	62.7	500.6	32.8	300.0	.296	.298	.5231
33	14.69	81.3	506.4	1312.	500.1	837.7	489.6	88.0	495.4	88.5	500.8	45.7	299.75	.406	.409	.5164
34	14.69	109.0	528.0	1962.	527.5	1305.	494.7	113.3	495.2	113.3	506.9	58.4	300.25	.559	.567	.5154
35	14.63	49.7	507.5	1044.	505.1	420.6	490.4	163.5	509.3	163.7	520.6	87.5	180.25	.780	.802	.5346
36	14.69	135.7	542.6	2164.	512.3	1309.	492.9	214.9	500.3	215.6	519.3	109.9	180.0	1.08	1.11	.5099
37	14.63	235.1	547.2	1950.	533.4	1005.	494.0	263.9	505.5	263.9	523.1	135.6	179.5	1.16	1.20	.5137
38	14.47	248.5	550.1	1632.	516.3	529.5	487.8	313.5	513.0	312.5	528.7	160.0	180.75	1.49	1.54	.5119

FLOW OF AIR THROUGH AN ORIFICE. Diameter of orifice = 0.6333 inch.

Number.	Barometer. (Lbs. per square inch.)	P_0.	T_0.	P_1.	T_1.	P_2.	T_2.	P_3 final.	T_3 final.	P_3 average.	T_3 average.	P_4	Duration of test in seconds.	G_c.	G_0.	$P_4 \div P_0$.
		Initial pressure in receiver. (Abs.)	Initial temperature in receiver. (Abs.)	Initial pressure in reservoir. (Abs.)	Initial temperature in reservoir. (Abs.)	Final pressure in reservoir. (Abs.)	Final temperature in reservoir. (Abs.)	Final pressure in receiver. (Abs.)	Final temperature in receiver. (Abs.)	Average pressure in receiver. (Abs.)	Average temperature in receiver. (Abs.)	Average pressure in orifice. (Abs.)		Lbs. of air through orifice per second, under conditions P_3 average, and T_3 average.	Lbs. of air through orifice per second, under conditions P_3 average, and 32° F.	Ratio of pressure in orifice, to pressure in receiver.
39	14.69	14.69	518.3	604.7	506.9	275.7	498.5	37.8	507.1	37.9	509.3	20.0	299.75	.270	.274	.5277
40	14.80	46.8	522.4	953 8	510.2	121.8	489.6	61.1	503.9	62.5	509.6	33.1	480.5	.462	.470	.5295
41	14.69	14.69	518.4	1395.	516.6	587.7	496.1	88.2	502.4	88.2	513.4	47.5	299.75	.634	.647	.5385
42	14.69	14.69	508.5	1364.	507.6	343.7	491.1	113.3	496.1	113.9	508.9	60.6	300.5	.837	.840	.5321
43	14 67	14.67	508.5	1056.	510.9	255 7	493 9	151.4	509.3	160.9	523 5	85.0	152.25	1.17	1.21	.5282
44	14.67	14.67	523.1	2403.	526.9	1009.7	494.5	213.7	500.3	214.6	520.1	111.9	.....	1.62	1.66	.5314
45	14.74	14 74	512 0	2092.	513.6	486.7	489 3	253.7	497.6	261.3	517.0	136.9	181.75	2.00	2.05	.5240
46	14.67	14 67	522.9	2305.	520.1	438.7	490.2	293.7	498.1	309.2	522 2	162.2	173.0	2.38	2.45	.5247

Hirn Tests.

The object of these tests is to show the interchange of heat between the steam and the walls of the cylinder during the different parts of the stroke.

A complete description of the manner of conducting such tests, together with the thermodynamic equations used in calculating the results, will be found in the Technology Quarterly, Vol. IX, pp. 43 to 50.

The tests here given form a part of a series which have been made on a 9″ – 16″ – 24″ x 30″ triple expansion engine of the Corliss type, made by the E. P. Allis Company.

The report of tests No. I to IV will be found in the Technology Quarterly, Vol. IX, and of tests V to XII in Vol. XIII.

These four tests were made with the engine running as a compound, the low pressure cylinder being cut out.

The dimensions of the engine are as follows:

High Pressure Cylinder.

Dia. of piston = 8.99″. Dia. of piston rod = 2.19″. Stroke = 30″.
Piston displacement: H. E. = 1.102 cu. ft.; C. E. = 1.037 cu. ft.
Clearance in % of P. D.: H. E. = 8.83; C. E. = 9.76.
Engine constant: H. E. = .004809; C. E. = .004524.

Intermediate Pressure Cylinder.

Dia. of piston = 16.01″. Dia. of piston rod = 2.19″. Stroke = 30″.
Piston displacement: H. E. = 3.495 cu. ft.; C. E. = 3.430 cu. ft.
Clearance in % P. D.: H. E. = 10.4; C. E. = 10.9.
Engine constant: H. E. = .01525; C. E. = .01497.

Low Pressure Cylinder.

Dia. of piston = 24.063″. Dia. of piston rod = 2.16″. Stroke = 30″.
Piston displacement: H. E. = 7.894 cu. ft.; C. E. = 7.831 cu. ft.
Clearance in % P. D.: H. E. = 12.18; C. E. = 12.27.
Engine constant: H. E. = .0345; C. E. = .03417.

Test Number.	XIII.	XIV.	XV.	XVI.
Duration of test, minutes	60	60	60	60
Total number of revolutions	5,193	5,192	5,027	5,042
Revolutions per minute	86.55	86.53	83.78	84.03
Steam consumption during test, pounds:				
Passing through cylinders	757.5	744 0	1085.0	1057.5
Condensation in h. p. jacket	46.6	45.5	47.2	49.6
in receiver jacket	74 4	67.0	91.0	92.6
in i. p. jacket	63 8	61 6	73.3	72.1
Total	942 3	918.1	1296.5	1271.8
Condensing water for test, pounds	21,345	20,574	28,973	30,768
Priming, by calorimeter	.8%	.7%	1.1%	1.0%
Temperature, Fahrenheit:				
Condensed steam	71.2	71.5	76.4	74.9
Condensing water, cold	46.4	46.3	46.1	46.1
Condensing water, hot	84 6	86.3	85.6	83.0
Pressure of the atmosphere, by the barometer, pounds per square inch	14.79	14.80	14.78	14.79
Boiler pressure, pounds per square inch, absolute	134.8	134.8	133 5	133.5
Vacuum in condenser, inches of mercury	25.86	25.59	25.61	25.59
Events of the stroke, per cent.:				
High-pressure cylinder —				
Cut-off, crank end	10.4	10.3	22.9	22.5
head end	8.5	8.4	23.6	22.2
Release, both ends	100 0	100.0	100.0	100.0
Compression, crank end	7.0	7.0	7.0	7.0
head end	9.0	9.0	9.0	9.0
Intermediate-pressure cylinder —				
Cut-off, crank end	28.0	28.0	21.0	20.5
head end	27.0	27.0	20 0	20.5
Release, both ends	100.0	100.0	100.0	100.0
Compression, crank end	7.0	10.0	7.0	10.0
head end	7.0	10 0	7 0	10.0
Absolute pressures in the cylinder, pounds per square inch:				
High-pressure cylinder —				
Cut-off, crank end	127.8	123.8	123.3	123.3
head end	122 8	120.3	119.7	120.6
Release, crank end	27.1	26.6	41.3	41.9
head end	22 8	22 6	39.3	38.0
Compression, crank end	27 6	25.5	44.7	44.6
head end	26.8	26 3	44 5	43.6
Admission, crank end	42.6	45.0	66.9	67.6
head end	53.8	55.3	93.7	90.0

Test Number.	XIII.	XIV.	XV.	XVI.
Intermediate-pressure cylinder —				
Cut-off, crank end	19.9	20.3	36.0	36.8
head end	20.1	20.6	35.4	35.4
Release, crank end	7.1	6.4	10.3	10.3
head end	6.5	6.3	8.9	9.0
Compression, crank end	2.4	2.5	3.6	3.2
head end	2.5	2.6	2.8	2.7
Admission, crank end	5.6	5.6	7.5	7.5
head end	7.2	7.2	7.8	7.8
Heat equivalents of external work, B. T. U. from areas on indicator diagram to line of absolute vacuum:				
High-pressure cylinder —				
During admission, $A\,W_a$, crank end	2.73	2.64	5.86	5.71
head end	2 25	2.33	6.22	5.89
During expansion, $A\,W_b$, crank end	8.87	8.92	9.90	9.67
head end	8 04	8.11	9.52	9.43
During exhaust, $A\,W_c$, crank end	4.54	4 62	7.53	7.28
head end	4.47	4.51	7.50	7.34
During compres'n $A\,W_d$, crank end	0.58	0.55	0 92	0.83
head end	0.74	0 68	1.38	1.11
Intermediate-pressure cylinder —				
During admission, $A\,W_a$, crank end	4.07	4.11	5.41	5.25
head end	4 09	4.10	5.10	5.15
During expansion, $A\,W_b$, crank end	4.98	4.98	8.78	8.78
head end	5 05	5.02	8 49	8.33
During exhaust, $A\,W_c$, crank end	1.51	1.64	2 17	2.25
head end	1.61	1.54	1.78	1 83
During compres'n, $A\,W_d$, crank end	0.17	0.18	0 30	0 23
head end	0.31	0.26	0.34	0.38
Quality of the steam in the cylinder. At admission and at compression the steam was assumed to be dry and saturated:				
High-pressure cylinder —				
At cut-off x_1	.656	.651	.740	.746
At release x_2	.850	.847	.889	.910
Intermediate-pressure cylinder —				
At cut-off x_1	.856	.889	.820	.856
At release x_2	.898	.859	.846	.882

Test Number.	XIII.	XIV.	XV.	XVI.
Interchanges of heat between the steam and the walls of the cylinders in B. T. U. Quantities affected by the positive sign are absorbed by the cylinder walls; quantities affected by the negative sign are yielded by the walls:				
High-pressure cylinder —				
Brought in by steam . Q . . .	86.2	84.7	127.3	123.8
During admission . . Q_a . . .	26 2	26 0	28.1	26.9
During expansion . . Q_b . . .	−18.4	−18.5	−21.7	−22.8
During exhaust . . . Q_c . . .	−10.3	−10.0	−9.6	−7.3
During compression . Q_d . . .	0.6	0 5	1.0	0.8
Supplied by jacket . . Q_j . . .	3 9	3 8	4.0	4.2
Lost by radiation . . Q_e . . .	1.8	1.8	1 8	1.8
First intermediate receiver —				
Supplied by jacket . . Q_{jR} . . .	6.2	5.6	7.8	7.9
Lost by radiation . . Q_{eR} . . .	1.3	1.3	1.3	1.3
Intermediate-pressure cylinder —				
Brought in by steam . Q' . . .	87.2	85 0	128 8	125.7
During admission . . Q'_a . . .	14 3	11.1	23 8	20.1
During expansion . . Q'_b . . .	−6.7	−1 6	−8 5	−8.5
During exhaust . . . Q'_c . . .	−10.1	−11 8	−18.8	−19.3
During compression . Q'_d . . .	0.2	0 3	0.3	0 3
Supplied by jacket . . Q'_j . . .	5.3	5.1	6.3	6.1
Lost by radiation . . Q'_e . . .	3.0	3.0	3.0	3.0
Total loss by radiation:				
By preliminary test . . ΣQ_e . .	6.1	6.1	6.1	6.1
By equation	8.8	4.0	8.1	6.5
Power and economy:				
Heat equivalents of works per stroke:				
High-pressure cylinder AW . . .	5.90	5.91	7.10	7.19
Int.-pressure cylinder AW' . . .	7.21	7.21	11.37	11.79
Totals	13.11	13.12	18.47	18.98
Total heat furnished by jackets . . .	15.3	14 4	18.1	18.3
Distribution of work:				
High-pressure cylinder	1.00	1.00	1.00	1.00
Intermediate-pressure cylinder . . .	1.22	1.22	1.64	1.60
Total horse-power	53 57	53 53	75.01	73.22
Steam per horse-power per hour . .	17.6	17.2	17.3	17.4
B. T. U. per horse-power per minute .	305.0	298 0	300.9	302 3
B. T. U. per horse-power per minute, 2 pounds absolute	302.7	295.4	299.6	300.8

Engine Tests.

The tests made on the Triple Expansion Engine run as a compound, the low pressure cylinder being cut out, show the economy of this engine when running under the following conditions:

(1) No jackets on the cylinders and none of the heating surface of the reheater used, the boiler pressure being approximately 100 pounds per square inch by the gauge.

(2) The same conditions as in (1), with the exception of the boiler pressure, which was approximately 120 pounds per square inch by the gauge.

The dimensions of this engine are given in connection with the Hirn tests. A description of the reheater has also been given in the Technology Quarterly, Vol. XI.

The Tandem Compound Engine has the high pressure cylinder only jacketed, and a coil of pipe is used to reheat the steam in the receiver. The tests show the economy of this engine when running under the following conditions:

(1) No jackets used on high pressure cylinder and coil not used in the receiver, the boiler pressure being approximately 100 pounds per square inch by the gauge.

(2) Jackets used on the high pressure cylinder and coil used in the receiver, the boiler pressure being approximately 120 pounds per square inch by the gauge.

The dimensions of this engine are:

	High.	Low.
Diameter of piston, inches	11	19
Diameter of piston rod, inches	1.63	2 13
Stroke, inches		15

All the tests were of 60 minutes' duration, indicator cards being taken at 5-minute intervals.

The plots, Figures 2 to 5, show the heat consumption per horse-power per minute reduced to 2 pounds absolute; one plot for each engine showing the variation of the heat consumption with the change of cut-off on the high pressure cylinder; the remaining plots showing the variation of the heat consumption with the indicated horse-power reduced to 2 pounds absolute.

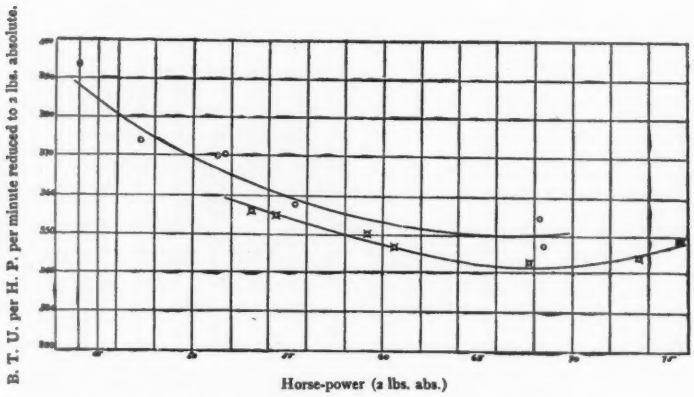

FIG. 2. — RESULTS OF TESTS ON A TRIPLE EXPANSION ENGINE RUN AS A COMPOUND, LOW-PRESSURE CYLINDER CUT OUT.

No jackets used on cylinder or on reheater. Upper curve, 100 lbs. boiler pressure; lower curve, 120 lbs.

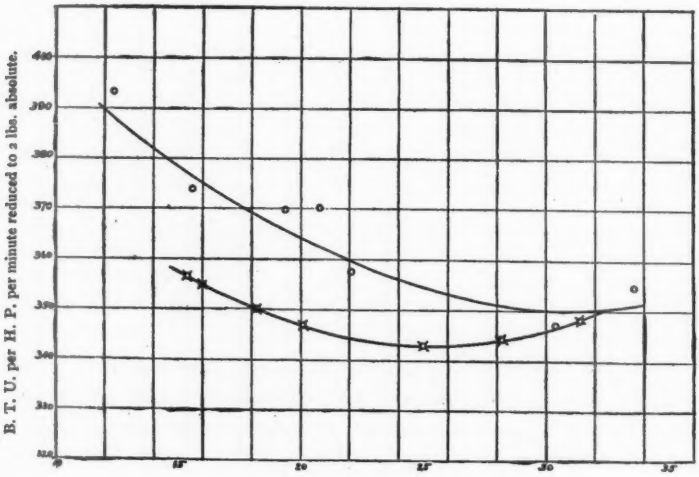

FIG. 3. — RESULTS OF TESTS ON TRIPLE EXPANSION ENGINE RUN AS A COMPOUND, LOW-PRESSURE CYLINDER CUT OUT.

No jackets used on cylinders or reheater. Upper curve, 100 lbs. boiler pressure; lower curve, 120 lbs.

TESTS ON A TRIPLE EXPANSION ENGINE. (Low-pressure cylinder cut out.)

Figures 2 and 3.

Date. 1901.	Horse-power, total. Corrected to 2 lbs. abs.	Steam per horse-power per hour.	Steam through cylinders per hour. (Lbs.)	Revolutions per minute.	Boiler pressure by gauge.	Pressure in first receiver by gauge.	Vacuum in condenser by mercury column. (Inches.)	Barometer. (Inches.)	Barometer. (Lbs. per sq. inch.)
Mar. 26	42.0	22.5	917	85.0	99.3	1.2	24.5	29.6	14.5
Mar. 29	47.3	20.9	981	85.3	99 8	2 0	25.2	29.6	14.5
Mar. 22	51.3	21.0	1,053	83.7	100.2	4.7	24.9	29.9	14.7
May 16	51.7	21.1	1,062	84.3	99.1	5.8	24.9	30.0	14.7
Mar. 19	55.4	19.9	1,099	83.5	99.6	6.3	26.1	30.3	14.9
Apr. 9	68.5	19.2	1,319	83.1	99.7	9.5	25.7	29.6	14.5
May 17	68.3	20.0	1,344	82.7	99.3	11.7	25.1	29.9	14.7
May 10	53.1	19.9	1,047	85 1	118.5	6.1	25.6	30.0	14.7
May 9	54.4	19.9	1,069	85.1	118.2	5.3	25.5	30.0	14.7
May 2	59.2	19.6	1,146	85.1	118.7	8.0	25.0	29 6	14.5
May 7	60.6	19.3	1,163	84.4	118.3	8.3	25.3	29.7	14.6
Apr. 26	67.7	19.3	1,283	83.7	118.9	12.7	25.2	30.2	14.8
Apr. 25	73.5	19.2	1,397	83.4	119.0	11.0	25.1	29 8	14 6
May 6	75.6	19.4	1,455	82.8	118.4	22.5	25.2	29.8	14.6

TESTS ON A TRIPLE EXPANSION ENGINE. (Low-pressure cylinder cut out.) — *Continued.*

High-Pressure Cylinder.

Date. 1901.	Initial pressure.	Per cent. of cut-off.	Pressure at cut-off.	Pressure at release.	Pressure at compression.	Per cent. of steam in cylinders at cut-off.	Per cent. of steam in cylinders at release.	M. E. P., crank end.	M. E. P., head end.	Horse-power. (Indicated.)
Mar. 26	100.5	12.4	88.1	10.1	1.9	55.1	71.9	36.7	31.1	26.9
Mar. 29	102.4	15.7	79.9	13.3	2.3	60.3	77.1	42.9	36.9	31.7
Mar. 22	101.3	19.4	88 8	16.4	4.2	62.6	76.9	44.0	40.6	33.0
May 16	96.1	20.8	85.4	16.1	6.0	63.7	76.3	43.3	39.7	32.6
Mar. 19	101.4	22.1	91.4	18.5	7.9	66.9	78.2	44.8	44.3	34.7
Apr. 9	100.9	30.3	90.6	26.2	10.7	70.1	78.8	51.1	51.5	39.8
May 17	97.6	33.6	89.7	27.0	12.9	73.2	78.5	50.3	50.8	39.0
May 10	113.1	15.4	103.0	15.3	6.4	62.2	76.0	42.7	40.3	32.9
May 9	116.8	16.0	104.9	15.9	6.3	63 5	76.0	45.6	42.0	35.8
May 2	116 9	18.1	108 5	18.7	8.1	65.4	76.5	49.4	44.3	37.1
May 7	117.1	20.0	105.2	19.8	9.3	66 9	77.1	50 7	47.3	38.6
Apr. 26	117.0	24.9	103.2	25.9	14.7	68 7	80.6	52.9	48.6	39.6
Apr. 25	116.7	28.2	105.7	28.9	14.4	70.6	79.0	54.9	54.9	42.7
May 6	117.5	31.9	111.8	33.6	23.0	75.8	81.1	52.4	51.2	40.1

TESTS ON A TRIPLE EXPANSION ENGINE. (Low-pressure cylinder cut out.) — *Concluded.*

INTERMEDIATE PRESSURE CYLINDER USED AS LOW-PRESSURE CYLINDER.

DATE. 1901.	Initial pressure.	Per cent. of cut-off.	Pressure at cut-off.	Pressure at release.	Pressure at compression.	Per cent. of steam in cylinder at cut-off	Per cent. of steam in cylinder at release.	M. E. P. crank end.	M. E. P. head end.	Horse-power. (Indicated.)	B. T. U. per H. P. per minute, actual vacuum.	B. T. U. per H. P. per minute, reduced to 2 lbs. absolute.
Mar. 26	.6	38.9	—1.5	—8.8	—11.4	36.1	62.4	5.63	5.19	13.9	403.	394.
Mar. 29	1.5	20.0	—1.9	—8.9	—11.8	34.3	57.3	5.95	5.82	15.2	377.	374.
Mar. 22	3.7	18.8	0.1	—8.2	—11.6	34.7	60.0	7.05	6.56	17.2	376.	370.
May 16	5.0	17.5	2.5	—8.1	—11.4	35.6	60.9	7.35	6.61	17.8	377.	370.
Mar. 19	5.3	18.5	2.4	—7.9	—12.2	38.4	62.4	8.33	7.98	20.6	358.	358.
Apr. 9	9.7	27.5	4.4	—6.3	—12.4	46.2	61.0	11.46	11.49	28.9	347.	347.
May 17	12.1	23.0	6.8	—11.9	—11.3	44.0	62.2	11.72	10.98	28.4	358.	355.
May 10	5.9	18.8	1.3	—7.9	—11.7	37.6	64.6	7.98	7.36	19.7	359.	357.
May 9	4.8	20.3	—0.2	—8.0	—11.7	34.8	60.3	7.92	6.92	19.1	357.	355.
May 2	7.0	19.3	2.5	—7.4	—11.6	37.8	61.8	8.77	7.85	21.4	353.	350.
May 7	7.7	17.5	4.1	—7.8	—11.4	37.8	57.3	9.13	8.00	21.8	347.	347.
Apr. 26	13.2	19.8	5.8	—7.4	—11.2	40.5	56.0	10.92	10.37	26.9	347.	343.
Apr. 25	13.4	20.8	8.3	—5.5	—11.7	42.6	63.1	12.46	11.33	30.0	347.	344.
May 6	22.5	15.5	15.0	—5.3	—11.4	43.2	61.8	14.77	12.97	34.8	351.	349.

TESTS ON A 11"–19" x 15" TANDEM COMPOUND ENGINE.

Date.	Horse-power.	Steam per H. P. per hour, including jacket steam. (Lbs.)	Steam through cylinders per hour. (Lbs.)	Water by Jackets.		Revolutions per minute.	Boiler pressure by gauge.	Pressure in receiver.	Vacuum in condenser. (Inches of mercury.)	Barometer. (Inches.)	B. T. U. per H. P. per minute actual vacuum.	Horse-power reduced to 2 lbs. absolute.	B. T. U. per H. P per minute, reduced to 2 lbs. absolute.
				High jacket. (Lbs.)	Receiver coil. (Lbs.)								
Mar. 25	61.4	25.5	1,568	0	0	243.9	102.7	6.3	24.9	30.11	458	64.0	442
Mar. 26	65.3	24.4	1,591	0	0	243.6	103.0	6.1	24.5	29.60	436	67.9	423
Apr. 9	74.1	24.1	1,781	0	0	242.7	103.0	8.6	24.6	29.62	431	76.4	420
Feb. 28	76.5	23.6	1,806	0	0	239.9	102.0	8.0	25.4	30.12	424	78.0	417
Mar. 22	72.9	23.5	1,710	0	0	242.3	103.0	8.1	25.0	29.86	421	74.7	413
Mar. 8	75.0	23.4	1,754	0	0	241.8	102.7	9.2	24.5	30.07	417	78.9	401
Mar. 11	95.4	22.5	2,149	0	0	239.0	102.3	12.7	24.6	29.30	405	96.9	400
Mar. 28	90.7	21.9	1,985	0	0	241.3	102.9	10.4	24.6	29.37	393	92.5	387
Apr. 1	93.2	21.9	2,038	0	0	240.2	103.3	12.4	25.0	29.69	393	94.8	388
Mar. 18	94.6	22.3	2,113	0	0	240.6	102.8	13.0	25.0	29.97	401	96.9	393
Mar. 19	92.1	22.7	2,093	0	0	240.1	103.1	12.7	25.0	30.30	406	95.2	397
Mar. 4	107.2	21.4	2,297	0	0	236.6	101.3	15.1	25.1	29.94	385	109.0	380
Mar. 15	104.6	20.9	2,192	0	0	241.0	102.4	14.1	25 0	29.72	376	106.2	372
Mar. 29	106.7	20.9	2,233	0	0	238.3	103.0	14.5	25.0	29.58	376	108.0	373
Mar. 7	111.9	21.0	2,354	0	0	236 7	102.9	17.3	24.6	30.15	376	115.4	368
Mar. 5	113.3	20 7	2,342	0	0	236.4	102.6	16.6	24.8	29.51	371	114.8	368
Apr. 2	120.9	21.2	2,567	0	0	234.8	103.0	19.0	24.9	30.07	380	123.6	375
Apr. 4	127.6	20.8	2,651	0	0	232.1	102.7	21.8	24.6	29.50	373	129.6	369
May 16	138.6	20.8	2,893	0	0	231.1	102.0	25.0	25.1	30.05	374	140.7	371
May 13	55.4	26.4	1,386	46.6	29.4	243.4	123.8	4.2	24.9	29.69	471	57.2	458
Apr. 29	73.7	22.9	1,617	38.8	34.5	244.0	122.0	7.3	25.6	30.17	410	74.9	405
May 2	84.6	21.9	1,780	33.3	37.2	243.4	121.2	9.9	24.5	29 59	390	85.9	387
May 9	86.4	22.1	1,821	46.0	37.0	242.0	121.2	10.6	25.1	30.00	393	88.5	386
Apr. 26	91.5	21.1	1,847	46.1	35.5	243.8	121.9	11.7	25.7	30.18	377	92.6	374
May 6	108.4	20.9	2,177	43.7	45.3	240.8	121.5	15.2	25.2	29.77	374	109.7	370
May 7	111.9	20.9	2,254	44.3	42.7	240.6	121.5	16.6	24.8	27.70	373	113.9	369
Apr. 12	129 8	20.1	2,523	41.6	42.8	236.0	124.6	21.4	25.4	30.04	360	131.0	358
Apr. 22	132.9	20.5	2,603	49.4	72.6	237.7	121.3	21.4	25.0	30.00	366	135.2	361
Apr. 23	129.4	20.3	2,543	47.0	44.2	238.6	120.9	20.2	24.9	30.13	363	132.1	358
Apr. 15	131.4	20.3	2,576	46.1	49.4	238.2	124.4	20.9	25.3	30.02	364	133.0	361
Apr. 16	137.3	20.1	2,675	38.4	48.5	237.3	124.0	23.4	25.1	30.04	360	139.3	356
May 14	142.9	19.9	2,763	36.6	47.4	239.1	123.9	24.5	25.9	29.97	357	143.9	355
Apr. 11	132.1	20.8	2,655	34.1	49.9	231.1	103.0	23.8	24.5	29.97	369	135.6	363

TESTS ON A 11″–19″ x 15″ TANDEM COMPOUND ENGINE. — *Continued.*

HIGH-PRESSURE CYLINDER.

DATE.	Initial pressure.	Per cent. of cut-off.	Pressure at cut-off.	Pressure at release.	Pressure at compression.	Per cent. of steam in cylinder at cut-off.	Per cent. of steam in cylinder at release.	M. E. P. Crank end.	M. E. P. Head end.	Horse-power.
Mar. 25	92.3	11.0	68.3	18.9	16.1	49.5	67.9	14.9	15.5	26.4
Mar. 26	93.1	11.4	68.2	19.9	16.7	49.0	68.2	15.6	16.4	27.8
Apr. 9	95.2	12.5	71.8	20.7	19.7	53.2	68.5	17.0	18.2	30.4
Feb. 28	95.3	14.3	74.5	23.0	33.8	52.7	68.2	18.8	20.9	33.9
Mar. 22	96.0	14.7	71.9	22.2	19.0	54.9	70.7	19.4	20.6	34.5
Mar. 8	96.7	16.0	69.0	21.0	20 5	54.9	70.9	18.9	21.5	34.8
Mar. 11	97.0	20 1	76.2	28.7	24.4	56.0	72.8	23.6	26.9	43.0
Mar. 28	101.0	20.3	76.7	27.1	18.6	61.1	74.9	23.4	26.6	43.0
Apr. 1	98.0	20.5	75.7	25.8	19.7	59.2	72.8	23.1	24.1	40.4
Mar. 18	97.2	21.3	74.3	28.1	24.6	58.0	73.6	23.7	25 8	42.4
Mar. 19	98.0	21.6	73.0	28.5	22.0	57.9	72.3	23.0	25.8	41.7
Mar. 4	98.3	24.5	82.9	30.4	29.6	63.9	74.3	25.6	31.1	47.8
Mar. 15	101.3	26.6	74.6	30.5	24.4	65.5	76.5	27.1	30.0	49.0
Mar. 29	100.4	27.3	76.9	31.7	27.7	66.0	76.3	27.6	29.8	48.7
Mar. 7	100.4	28.0	77.3	33.8	31.3	64.4	77.7	28.5	31.4	50.5
Mar. 5	98.7	29.8	73.3	34.9	30.9	64.4	78.8	28.6	31.9	50.9
Apr. 2	101.5	35.1	75.7	37.3	31.9	64.9	73.5	28.8	33.9	52.5
Apr. 4	102.8	38.5	79.3	40.4	31.5	73.0	79.8	30.7	35.6	54.8
May 16	100.6	48.0	75.2	44.2	35.7	77.6	81.6	34.1	37.8	59.2
May 13	114.6	5.8	86.8	17.2	7.7	51.6	67.9	13.7	13.4	23.5
Apr. 29	113.1	9.1	86.3	20.1	13.0	52.9	69.9	18.2	17.1	30.7
May 2	116.3	13.7	83.4	24.6	21.3	56 3	71.9	23.0	22.0	39.0
May 9	114.3	14.9	83.5	26.1	20.9	58.0	72.3	20.3	22.8	37.1
Apr. 26	115.3	15.4	86.7	26.7	24.6	59.0	73.1	21.2	23.3	38.6
May 6	117.5	19.7	87.3	32.8	25.9	54.6	86.9	26.2	28.7	47.0
May 7	117.3	21.7	86.6	32.2	27.4	61.2	73.4	26.8	30.5	49.2
Apr. 12	122.4	25.4	90.1	39.9	35.8	63.1	81.6	31.8	34.2	55.5
Apr. 22	119 4	26.8	92.9	40.3	39.5	65.2	81.0	33.1	35.8	58.3
Apr. 23	120.9	27.0	94.7	39.5	32.5	67.2	77.4	30.5	34.9	55.6
Apr. 15	121.2	28.5	92.2	38.8	36.6	67.4	75.3	31.2	36.8	57.7
Apr. 16	120.8	28.8	92.1	40.9	35.0	66.3	77.7	32.2	36.5	58.1
May 14	121.5	34.3	92.4	42.4	33.3	73.1	78.1	33.2	38.7	61.2
Apr. 11	101.3	41.1	78.6	41.6	37.6	75.1	80.6	30.1	36.0	54.5

TESTS ON A 11″–19″ x 15″ TANDEM COMPOUND ENGINE. — *Concluded.*

LOW-PRESSURE CYLINDER.

DATE.	Initial pressure.	Per cent. of cut-off.	Pressure at cut-off.	Pressure at release.	Pressure at compression.	Per cent. of steam in cylinder at cut-off.	Per cent. of steam in cylinder at release.	M. E. P. Crank end.	M. E. P. Head end.	Horse-power.
Mar. 25	5.4	27.5	—0.24	—7.48	—10.7	52.5	60.5	6.7	6.7	35.0
Mar. 26	5.4	"	0.96	—6.45	—10.7	53.3	66.3	7.3	7.1	37.5
Apr. 9	8.6	"	2.14	—5.96	—10.5	52.8	62.8	8.3	8.5	43.7
Feb. 28	...	"	....	....	....	....	....	8.2	8.4	42.5
Mar. 22	6.6	"	0.81	—6.34	—10.8	51.1	63.4	7.6	7.3	38.4
Mar. 8	7.9	"	1.51	—5.9	—10.3	51.6	64.9	7.9	7.7	40.2
Mar. 11	12.4	"	5.23	—4.06	—10.3	51.1	61.9	10.5	10.1	52.4
Mar. 28	10.1	"	3.96	—4.96	—10.5	52.4	62.3	9.4	9.2	47.8
Apr. 1	12.0	"	5.07	—4.16	—10.5	53.9	65.9	10.6	10.1	52.9
Mar. 18	12.1	"	5.20	—4 50	—10.6	53.0	62.7	10.4	10.0	52.1
Mar. 19	12.6	"	4.75	—4.75	—10.2	52.3	62.3	10.1	9.6	50.4
Mar. 4	15.5	"	7.06	—3.46	—10.6	52.6	63.0	11.8	11.8	59.4
Mar. 15	13.5	"	6.00	—3 80	—10.3	52.8	63.9	11.1	10.6	55.6
Mar. 29	14.3	"	7.07	—3.48	—10.4	53.9	63.7	11.6	11.3	58.0
Mar. 7	17.0	"	8.17	—2.76	—10.1	53.6	64.6	12.2	12.2	61.4
Mar. 5	16.5	"	8.24	—2.63	—10.1	53.4	64.6	12.4	12.4	62.3
Apr. 2	19.3	"	10.30	—2.02	—10.0	53.3	62.5	13.7	13.7	68.4
Apr. 4	20.8	"	10.95	—1.02	—10.2	52.2	63.7	14.9	14.6	72.8
May 16	24.8	"	13.55	—0.93	—9 9	52.6	59.5	16.4	15.9	39.1
May 13	3.7	"	—1.51	—7.11	—10.7	52.9	69.1	6.2	6.2	31.9
Apr. 29	7.4	"	1.08	—6.13	—11.4	55.0	70.8	8.5	8.0	43.0
May 2	12.5	"	2.70	—5.95	—10.4	54.5	62.8	8.9	8.7	45.6
May 9	10.3	"	3.57	—5.10	—10.5	56.3	68.1	9.6	9.6	49.3
Apr. 26	12.9	"	4.25	—4.65	—11.3	58.9	72.4	10.2	10.2	52.9
May 6	14.5	"	7.15	—3.11	—10.28	55.8	68.0	12.3	11.7	61.3
May 7	17.6	"	7.95	—2.60	—10.59	56.2	69.1	12.4	12.1	62.7
Apr. 12	20.5	"	11.1	—1.31	—10.9	56.9	68.2	14.9	14.7	74.3
Apr. 22	20.0	"	10.9	—1.16	—10.7	55.0	74.6	15.1	14.4	74.6
Apr. 23	20.1	"	11.2	—1.27	—10.5	56.8	68.3	15.0	14.1	73.8
Apr. 15	20.4	"	11.3	—1.02	—10.5	56.3	68.5	14.7	14.4	73.7
Apr. 16	22.0	"	12.2	0.75	—10.7	56.0	73.8	15.5	15.9	79.2
May 14	24.5	"	12.9	—0.38	—10.3	55.7	66.7	16.4	15.7	40.1
Apr. 11	23.4	"	13.3	—0.30	—10.2	56.7	67.2	16.0	15.6	77.7

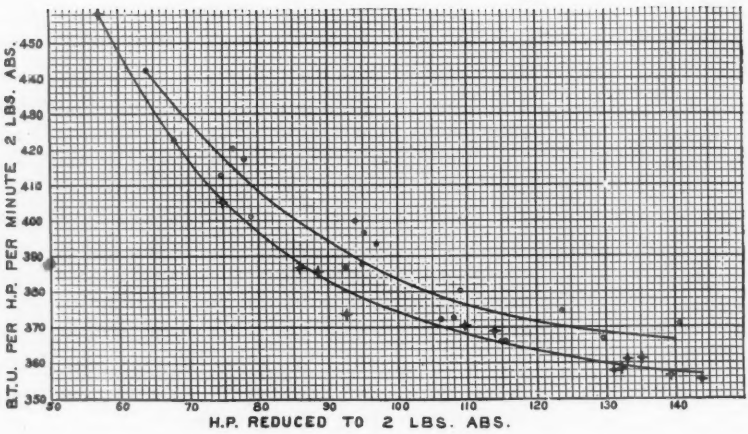

FIG. 4. — RESULTS OF TESTS ON A TANDEM COMPOUND ENGINE.

Upper curve, 100 lbs. boiler pressure (gauge); no jackets used.
Lower curve, 120 lbs. boiler pressure. Jackets on high-pressure cylinder and receiver.

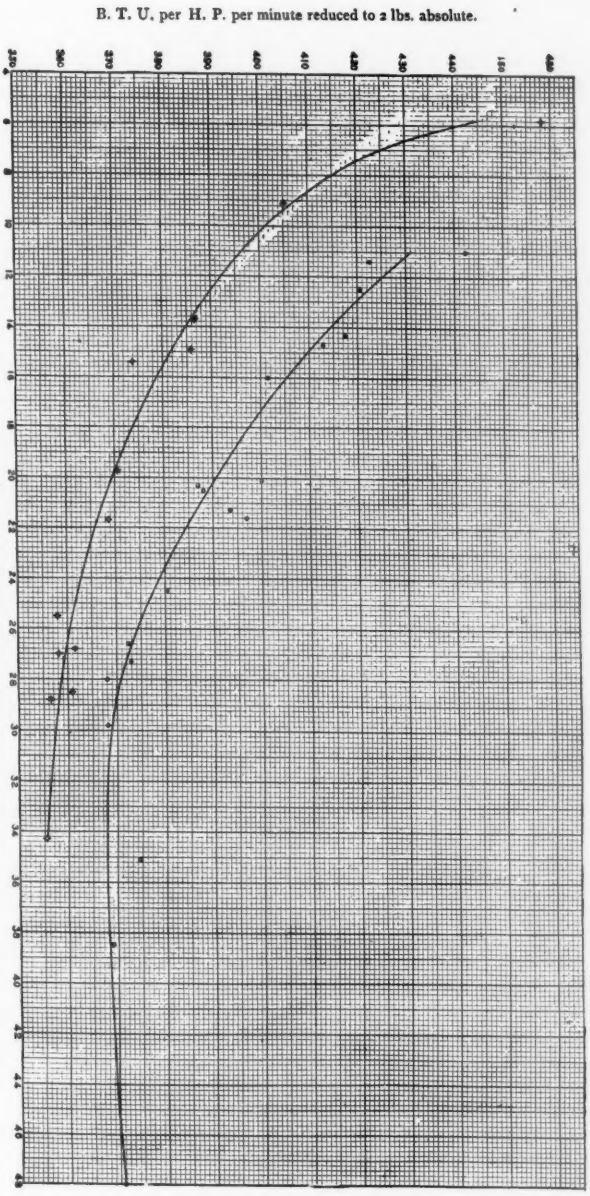

FIG. 5.— RESULTS OF TESTS ON TANDEM COMPOUND ENGINE.

Upper curve, 100 lbs. pressure (gauge), no jackets used. Lower curve, 130 lbs. pressure (gauge), jackets used on high-pressure cylinder and receiver.

Water Ejector Tests.

The following tests were made on a Hancock Ejector, size No. 6, which was fitted with a 1-inch feed pipe and with 2-inch suction and discharge pipes. The feed water was measured by means of a calibrated tank. A small steam pump was used for forcing the water through the ejector. The amount of water discharged was determined by weighing. The pressure heads at entrance, suction, and discharge were found from the readings of Bourdon gauges. The duration of every test was 30 minutes, and observations were taken at 2-minute intervals.

TESTS ON A WATER EJECTOR, 1901.

Number of test.	Entrance head. (Feet.)	Lift at suction. (Feet.)	Lift at discharge. (Feet.)	Water fed in 30 minutes.	Water lifted in 30 minutes.	Work done at entrance. (Foot-pounds per minute.)	Work done at discharge. (Foot-pounds per minute.)	Working efficiency. (Per cent.)
1	112.3	2.7	8.0	6,210	4,320	23,250	1,550	4.0
2	114.8	2.7	7.5	6,330	3,440	24,230	890	3.7
3	117.8	2.8	7.2	6,450	2,000	25,340	670	2.7
4	137.8	3.1	8.6	6,920	6,210	31,780	2,410	7.6
5	143.8	2.9	10.0	6,950	6,330	33,340	2,710	8.1
6	150.6	2.8	9.6	7,110	6,860	35,710	2,830	7.9
7	171.1	3.2	13.9	7,650	6,800	43,600	3,870	8.9
8	171.5	3.0	13.0	7,320	7,460	41,820	3,990	9.5
9	173.6	2.2	11.4	7,510	8,140	43,430	3,660	8.4
10	176.9	2.8	11.8	7,640	8,360	45,020	4,080	9.1
11	185.2	2.8	11.8	7,780	8,570	48,060	4,190	8.7
12	189.1	3.0	12.6	7,860	8,080	49,570	5,190	8.5
13	192.2	3.2	12.6	7,930	8,900	50,760	4,670	9.2
14	192.7	2.1	10.7	7,800	8,470	50,130	3,600	7.2
15	196.3	2.9	14.1	8,230	9,380	54,870	5,320	9.7
16	207.1	2.9	12.7	7,780	7,350	53,740	3,820	7.1
17	228.5	3.3	14.8	8,470	9,820	64,550	5,920	9.2

Tests on a Portable Device for Measuring Water under Pressure.

The apparatus consists of 2 feet of 4-inch steam pipe, to the discharge end of which a flange was screwed. Between this flange and a second one bolted to it was inserted a brass plate containing a standard orifice. The apparatus is shown in Figure 6.

The water was supplied to this orifice pipe through a $2\frac{1}{2}$-inch supply pipe. To determine the pressure acting on the orifice, the orifice pipe was tapped 7 inches behind the brass plate. The pressure was transmitted from this section through suitable piping to a mercury column the scale of which read pounds per square inch.

These pressure readings were corrected for temperature. The water used was measured in a calibrated tank of 250 cubic feet capacity. The coefficients were obtained by substituting in the formula $Q = C\ A\ \sqrt{2gh}$, where (Q) is the cubic feet per second, (C) is the coefficient of discharge, and (A) is the area of orifice in square feet (.003595), $(g) = 32.2$, and (h) is the head as calculated from the pressure, velocity head being negligible.

The temperature of the water varied between 16° and 20° Centigrade.

TESTS ON A DEVICE FOR MEASURING WATER UNDER PRESSURE.

Duration of test. (Minutes.)	Cubic feet of water during test.	Cubic feet of water per second.	Pressure. (Lbs. per sq. inch.)	Head as calculated from pressure.	Coefficient of discharge.
30	144.1	.0801	9.2	21.25	.602
30	188.2	.1045	15.68	36.21	.602
30	207.7	.1154	19.10	44.15	.602
30	208.2	.1157	19.31	44.62	.600
20	160.2	.1335	26.13	60.39	.595
20	169.4	.1411	28.56	65.98	.603
20	176.7	.1472	29.89	69.08	.600
25	228.4	.1523	33.76	78.63	.598
24	228.8	.1589	36.24	83.76	.602
20	194.7	.1622	37.59	86.80	.604
20	210.2	.1752	44.04	101.7	.602
18	193.6	.1792	46.12	106.6	.602
20	216.4	.1803	46.39	107.3	.604
18	213 0	.1972	55.62	128.5	.603

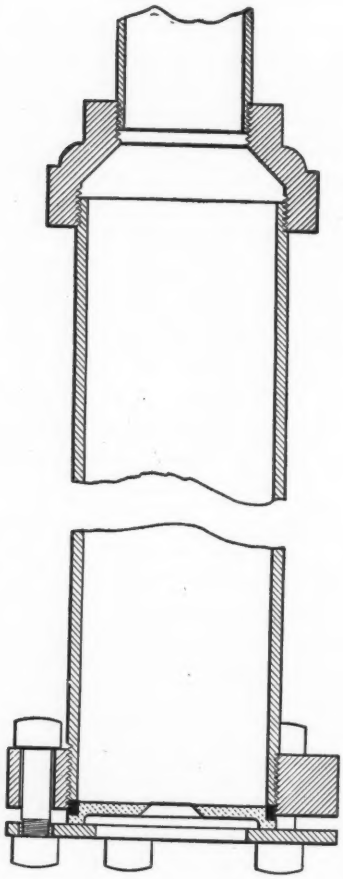

FIG. 6. — PORTABLE DEVICE FOR MEASURING WATER UNDER PRESSURE.

Number of test.	Diameter of cross section. (Ins.)	Distance between jaws. (Ins.)	Gauged length. (Ins.)	Elastic limit. (In.-lbs.)	Outside fiber stress at elastic limit. (Lbs. per sq. in.)	Maximum twisting moment. (In.-lbs.)	Apparent outside fiber stress as calculated from maximum twisting moment. (Lbs. per sq. in.)	Limits of loads for calculating shearing modulus of elasticity. (In.-lbs.)	Angle of twist for difference of loads used in calculating shearing modulus of elasticity.	Shearing modulus of elasticity. (Lbs. per sq. in.)	Number of turns between jaws at fracture.	Turns per foot between jaws at fracture.
1	1.75	59.0	30	19,800	18,720	67,140	63,460	3,600—19,800	2° 46′ 50″	11,180,000	10.55	2.15
2	1.75	56.5	30	21,240	20,180	70,660	67,160	1,800—21,240	3° 16′ 10″	11,110,000	10.30	2.19
3	1.75	53.5	30	21,240	20,180	64,170	60,990	1,800—21,240	3° 19′ 30″	11,440,000	10.40	2.33
4	1.75	52.0	30	21,240	20,180	66,105	62,820	1,800—21,240	3° 15′ 40″	11,130,000	9.25	2.13
5	1.75	51.3	30	21,960	20,860	67,680	64,310	1,800— 9,000	1° 11′ 10″	11,330,000	9.00	2.11
6	1.75	48.0	30	21,240	20,180	63,810	60,640	1,800—20,520	3° 7′ 30″	10,920,000	9.58	2.40
7	1.75	49.0	30	20,520	19,530	68,040	64,680	1,800—19,800	3° 0′ 40″	11,160,000	10.97	2.69
8	1.75	56.2	30	21,240	20,180	67,680	64,310	1,800—19,800	2° 58′ 10″	11,320,000	10.81	2.31
9	1.75	54.5	30	21,240	20,180	65,520	62,260	1,800— 9,000	1° 10′ 30″	11,440,000	9.12	2.01
10	1.75	48.5	30	20,520	19,490	68,760	65,350	1,800— 9,000	1° 3′ 0″	12,800,000	8.89	2.20
11	1.75	52.5	30	20,520	19,490	68,750	65,350	1,800—20,520	3° 6′ 50″	11,230,000	11.21	2.56
12	1.75	55.3	30	19,800	18,810	67,590	64,220	1,800—19,800	3° 1′ 30″	11,110,000	11.22	2.44
13	1.75	48.8	30	21,960	20,860	68,940	65,510	1,800—12,600	1° 45′ 0″	10,180,000	8.00	1.97
14	1.75	49.3	30	22,680	21,550	68,850	65,430	1,800—19,800	2° 54′ 40″	11,520,000	....	....
15	1.75	49.3	30	21,960	20,860	67,510	64,150	1,800—21,960	3° 15′ 20″	11,560,000	8.98	2.19
16	1.76	48.6	30	21,960	20,520	69,700	65,090	1,800—21,960	3° 16′ 10″	11,280,000	9.20	2.27
17	1.75	48.5	30	24,120	23,880	68,850	65,430	1,800—19,800	2° 53′ 30″	11,620,000	8.78	2.17

TORSION TESTS ON WROUGHT IRON, ROME BRAND.

Number of test.	Diameter of cross section. (Ins.)	Distance between jaws. (Ins.)	Gauged length. (Ins.)	Elastic limit. (In.-lbs.)	Outside fiber stress at elastic limit. (Lbs. per sq. in.)	Maximum twisting moment. (In.-lbs.)	Apparent outside fiber stress as calculated from maximum twisting moment. (Lbs. per sq. in.)	Limits of loads for calculating shearing modulus of elasticity. (In.-lbs.)	Angle of twist for difference of loads used in calculating shearing modulus of elasticity.	Shearing modulus of elasticity. (Lbs. per sq. in.)	Number of turns between jaws at fracture.	Turns per foot between jaws at fracture.
1	1.78	49.5	30	18,360	16,580	61,200	55,270	1,800—14,400	2° 8′ 40″	10,250,000	8.41	2.04
2	1.75	49.5	30	14,400	13,680	57,600	54,730	1,800—14,400	1° 58′ 10″	11,980,000	7.36	1.75
3	1.75	48.7	30	12,600	11,970	57,960	55,070	1,800—12,600	1° 48′ 50″	11,120,000	8.83	2.14
4	1.74	49.0	30	12,600	12,180	58,500	56,570	1,800—12,600	1° 48′ 0″	9,105,000	7.95	1.95
5	1.77	49.5	30	15,480	14,220	59,400	54,560	1,800—15,480	2° 28′ 0″	9,897,000	7.34	1.78
6	1.75	51.0	30	13,320	12,660	58,860	55,930	1,800— 9,000	1° 10′ 10″	11,490,000	8.11	1.91
7	1.76	49.0	30	13,680	12,780	57,680	53,860	1,800—10,800	1° 27′ 20″	11,730,000	7.03	1.76
8	1.76	49.0	30	14,040	13,110	58,320	54,460	1,800—12,600	1° 47′ 20″	11,010,000	7.74	1.90

TORSION TESTS ON BESSEMER STEEL ROD, COPPERED.

Number of test.	Diameter of cross section. (Ins.)	Distance between jaws. (Ins.)	Gauged length. (Ins.)	Elastic limit. (In.-lbs.)	Outside fiber stress at elastic limit. (Lbs. per sq. in.)	Maximum twisting moment. (In.-lbs.)	Apparent outside fiber stress as calculated from maximum twisting moment. (Lbs. per sq. in.)	Limits of loads used in calculation of shearing modulus of elasticity. (In.-lbs.)	Angle of twist for difference of loads used in calculation of shearing modulus of elasticity.	Shearing modulus of elasticity. (Lbs. per sq. in.)	Number of turns between jaws at fracture.	Turns per inch between jaws at fracture.
1	0.3440	11.0	5	310	39,000	610	76,300	10—310	5° 27′ 30″	11,466,000	6.95	0.63
2	0.3440	10.8	5	300	38,000	598	74,800	50—250	3° 40′ 30″	11,340,000	18.32	1.74
3	0.3440	10.8	5	325	41,000	597	74,700	100—325	4° 7′ 0″	11,400,000	10.90	1.01
4	0.3435	10.5	5	325	41,000	635	79,800	100—300	3° 35′ 30″	11,700,000	19.35	1.84
5	0.3434	10.5	5	350	44,000	625	78,600	100—300	3° 36′ 30″	11,600,000	6.62	0.63
6	0.3440	10.5	5	375	47,000	620	77,500	100—350	4° 42′ 0″	11,100,000	17.90	1.70
7	0.3440	10.5	5	325	41,000	645	81,300	100—300	3° 34′ 30″	11,800,000	18.65	1.78
8	0.3435	10.5	5	350	44,000	613	79,500	100—300	3° 51′ 0″	10,700,000	16.22	1.54
9	0.3437	10.4	5	275	34,000	610	76,500	100—275	3° 31′ 30″	11,300,000	21.55	2.07
10	0.3438	11.3	5	300	38,000	603	76,500	100—250	3° 46′ 30″	11,300,000	20.82	1.82
11	0.3437	11.3	5	270	34,000	543	68,100	100—270	3° 6′ 30″	11,400,000	19.81	1.75
12	0.3435	11.5	5	260	33,000	605	76,000	100—260	3° 14′ 30″	10,300,000	20.58	1.79
13	0.3435	11.5	5	230	29,000	595	74,800	100—230	2° 18′ 15″	11,800,000	21.89	1.90
14	0.3436	11.3	5	240	30,000	601	74,700	100—200	2° 57′ 30″	10,700,000	20.58	1.82
15	0.3436	11.3	5	230	29,000	601	75,400	100—230	2° 35′ 30″	10,500,000	19.28	1.71
16	0.3435	10.3	5	370	46,000	617	77,500	100—350	4° 38′ 30″	11,300,000	15.30	1.49
17	0.3435	11.0	5	360	45,000	623	78,300	100—350	4° 21′ 45″	12,000,000	4.33	0.39
18	0.3437	10.3	5	375	47,000	710	76,700	100—335	4° 12′ 20″	11,700,000	7.75	0.74
19	0.3438	10.7	5	410	51,000	625	78,400	100—300	3° 45′ 30″	11,100,000	12.56	1.22
20	0.3435	10.5	5	400	50,000	695	87,100	100—300	3° 33′ 20″	11,800,000	8.58	0.80
21	0.3438	10.6	5	440	55,000	675	84,800	100—300	3° 33′ 40″	11,800,000	10.10	0.96
22	0.3440	10.8	5	375	47,000	662	83,000	100—300	3° 39′ 55″	11,400,000	16.00	1.51
23	0.3437	10.5	5	350	44,000	645	80,700	100—300	3° 48′ 20″	10,900,000	1.48	0.14
24	0.3434	10.5	5	350	44,000	764	95,800	100—300	3° 33′ 35″	11,700,000	18.70	1.78
25	0.3436	10.5	5	350	44,000	610	76,500	100—300	3° 36′ 10″	11,600,000	16.73	1.59
26	0.3435	11.0	5	375	47,000	675	84,900	100—300	3° 31′ 30″	11,900,000	7.06	0.67
27	0.3434	10.5	5	350	44,000	622	78,500	100—300	3° 46′ 15″	11,200,000	5.01	0.46
28	0.3437	10.5	5	325	40,000	600	74,400	100—300	3° 51′ 30″	10,700,000	12.00	1.17
29	0.3434	10.5	5	350	44,000	610	77,000	100—300	3° 47′ 15″	11,100,000	9.16	0.85
30	0.3430	10.3	5	350	44,000	610	77,000	100—300	3° 43′ 15″	11,400,000	5.05	0.48
31	0.3430	10.5	5	350	44,000	610	77,000	100—300	3° 40′ 0″	11,500,000	9.56	0.91
32	0.3430	10.5	5	325	41,000	616	77,700	100—300	3° 16′ 15″	12,000,000	1.30	0.14
33	0.3430	10.5	5	350	44,000	610	77,000	100—300				
34	0.3430	10.5	5	325	41,000	595	75,100	100—300				
35	0.3430	9.0	5	350	44,000	575	73,600	100—300				

BEAMS.

TRANSVERSE TESTS ON HARD PINE BEAMS.

Number of test.	Width and depth of specimen. (Ins.)	Distance between supports. (Feet and inches.)	Limits of loads for calculation of modulus of elasticity. (Lbs.)	Deflections for difference of loads used in calculation of modulus of elasticity. (Ins.)	Modulus of elasticity. (Lbs. per sq. in.)	Breaking load. (Lbs.)
693	4 x 12¼	13—0	1,000— 7,000	0.4033	1,920,000	18,400
694	4 x 12¼	13—0	1,000— 7,000	0.3815	2,030,000	21,780
695	3⅞ x 11⅞	15—0	1,000— 5,000	0.5252	1,947,000	16,620
697	3⅛ x 11⅛	14—0	1,000—10,600	0.9748	1,728,000	18,110
698	4⅛ x 12¼	13—6	3,000— 7,000	0.3641	1,540,000	16,210
700	3⅞ x 12¼	13—0	500— 6,500	0.4740	1,588,000	10,110
712	4 x 12¼	15—0	1,000— 9,000	0.7393	2,147,000	20,410
713	4 x 12	16—0	1,000— 9,000	0.9353	2,330,000	20,100
714	4 x 12	15—0	1,000—11,000	1.0898	1,935,000	17,900
715	4⅛ x 12¼	15—0	1,000— 7,000	0.4404	2,394,000	22,600
716	4⅛ x 12⅛	15—0	1,000—15,000	1.2947	1,955,000	22,100

TRANSVERSE TESTS ON HARD PINE BEAMS. — *Concluded.*

Number of test.	Weight of beam. (Lbs.)	Modulus of rupture. (Lbs. per sq. in.)	Maximum intensity of longitudinal shear. (Lbs. per sq. in.)	Manner of failure.	Manner of loading.	Remarks.
693	220	7,260	287	By longitudinal shear.	At centre.	
694	220	8,535	337	By longitudinal shear.	"	Crippled slightly on top also.
695	250	9,115	293	By tension.	"	
697	220	8,175	292	By tension.	"	Two large knots near bottom at middle.
698	215	6,405	244	By tension.	"	
700	200	3,944	160	By tension.	"	
712	230	9,230	316	By longitudinal shear.	"	
713	265	10,330	318	By tension.	"	
714	255	8,450	284	By longitudinal shear.	"	
715	285	10,470	323	By longitudinal shear.	"	Large crack near top.
716	245	9,217	319	By tension.	"	Broke in two; brittle and dry.

TRANSVERSE TESTS ON SPRUCE BEAMS.

Number of test.	Width and depth of specimen. (Ins.)	Distance between supports. (Feet and inches.)	Limits of loads for calculation of modulus of elasticity. (Lbs.)	Deflections for difference of loads used in calculation of modulus of elasticity. (Ins.)	Modulus of elasticity. (Lbs. per sq. in.)	Breaking load. (Lbs.)
696	3 x 10	13—0	2,000— 4,000	0.5875	1,076,000	8,300
699	2⅞ x 9 11/16	14—0	400— 2,800	0.6528	1,543,000	6,490
701	2⅞ x 10	13—0	200— 1,600	0.3554	1,359,000	7,360
702	2⅞ x 10	13—6	600— 3,100	0.6668	1,449,000	5,780
703	5⅛ x 5⅛	14—0	400— 2,400	1.5414	1,291,000	4,990
704	5 1/16 x 6	13—6	600— 2,100	1.2579	1,031,000	3,900
705	2⅞ x 9⅛	13—6	500— 2,000	0.3089	2,024,000	7,240
706	2⅞ x 10	13—0	500— 4,000	0.8635	1,335,000	7,200
707	5⅛ x 6	13—0	400— 3,200	1.5200	1,377,000	5,200
708	2⅞ x 9⅛	13—0	500— 3,500	0 8220	1,306,000	7,290
709	2⅞ x 9⅛	13—0	500— 3,500	0.6610	1,561,000	9,060
710	2⅞ x 10	13—0	500— 3,500	0.6480	1,594,000	7,520
711	6 x 12	15—0	1,000— 8,000	0.7253	1,358,000	17,000
717	6 x 12	15—0	1,000— 6,000	0.5376	1,308,000	12,400
718	5⅛ x 12	15—0	1,000—10,000	0.9688	1,363,000	17,150
719	6 x 12	14—0	3,000—11,000	0 8289	1,103,000	17,100
691	4 x 12	19—0	1,000— 2,500	0.4350	1,487,000	9,460
692	2⅞ x 10	13—0	200— 1,400	0.3110	1,271,000	5,920

TRANSVERSE TESTS ON SPRUCE BEAMS.—*Concluded.*

Number of test.	Weight of beam. (Lbs.)	Modulus of rupture. (Lbs. per sq. in.)	Maximum intensity of longitudinal shear. (Lbs. per sq. in.)	Manner of failure.	Manner of loading.	Remarks.
696	100	3,770	210	.....	At centre.	Buckling prevented breaking.
699	90	5,800	173	By tension.	"	
701	90	6,310	203	By tension.	"	
702	85	5,145	160	By tension.	"	
703	110	6,270	110	By tension.	"	
704	105	4,695	89	By tension.	"	
705	85	6,770	205	By tension.	"	
706	90	5,885	190	By tension.	"	
707	100	5,810	113	By tension.	"	Broke in two; dry and brittle.
708	80	6,385	203	By tension.	"	
709	85	7,570	240	By tension.	"	
710	100	6,445	208	By tension.	"	
711	275	5,355	180	By tension.	"	
717	245	3,915	132	By tension.	"	Warped considerably; large crack on one side.
718	230	5,630	190	By crushing on top.	"	Large crack along top corner.
719	245	5,020	180	By crushing on top.	"	
691	220	5,680	150	By tension.	"	
692	80	4,840	156	By tension.	"	

ROPE TESTS. — TENSION TESTS ON 3″ MANILA ROPE. (3 strands.)

TESTED OVER CAST IRON THIMBLE, 6″ DIAMETER.

Number of test.	Date.	Number of feet per pound.	Number of turns of one strand per foot.	Condition.	Location of break.	Maximum load.	Average strength. (Lbs.)	Efficiency of knot or splice. (Per cent.)	Kind of knot or splice used.
1	Oct. 18, 1899.	....	....	Splices wet. Centre of rope dry.	At centre.	9,915	9,375	100	Spliced eye at each end.
2	Oct. 18, "	....	....		" "	8,375			
3	Oct. 18, "	....	....		Upper splice.	8,535			
4	Oct. 18, "	....	....		Lower splice.	9,255			
5	Oct. 25, "	....	....		.....	8,035			
6	Nov. 2, "	....	....		At centre.	8,830			
7	Nov. 2, "	....	....		" "	9,895			
8	Nov. 8, "	....	....		" "	9,765			
9	Nov. 8, "	....	....		" "	8,405			
10	Nov. 10, "	....	....		" "	9,210			
11	Nov. 10, "	....	....		" "	12,380			
12	Nov. 27, "	....	....		Lower splice.	13,005			
13	Nov. 27, "	....	....		Upper splice.	12,740			
14	Nov. 20, "	3.53	4.3	Dry.	Middle knot	7,950	5,225	53	Englishman's tie in middle; timber hitch at each end.
15	Nov. 20, "	3.53	4.3	"	" "	4,380			
16	Apr. 2, 1900.	3.53	4.4	"	" "	3,890			
17	Apr. 5, "	3.53	4.4	"	" "	4,675			
18	Nov. 20, 1899.	3.53	4.0	"	" "	3,830			
19	Mar. 31, 1900.	3.53	....	"	" "	2,920	3,740	38	Weaver's knot in middle; timber hitch at each end.
20	Apr. 2, "	3.53	....	"	" "	3,885			
21	Oct. 24, "	3.86	4.0	"	" "	4,265			
22	Oct. 26, "	3.86	4.0	"	" "	3,810			
23	Nov. 20, 1899.	3.53	4.2	"	" "	5,575	4,085	41	Square knot in middle; timber hitch at each end.
24	Mar. 31, 1900.	3.53	4.4	"	" "	3,985			
25	Apr. 2, "	3.53	4.4	"	" "	3,855			
26	Oct. 22, "	3.81	4.0	"	" "	3,740			
27	Oct. 22, "	3.87	4.0	"	" "	3,275			

TENSION TESTS ON 3″ MANILA ROPE. (3 strands.)—*Continued.*

TESTED OVER CAST IRON THIMBLE, 6″ DIAMETER.

Number of test.	Date.	Number of feet per pound.	Number of turns of one strand per foot.	Condition.	Location of break.	Maximum load.	Average strength. (Lbs.)	Efficiency of knot or splice. (Per cent.)	Kind of knot or splice used.
28	Nov. 24, 1900.	3.71	4.3	Dry.	Lower knot.	6,060	6,420	65	Fisherman's bend at each end.
29	Nov. 26, "	3.81	4.0	"	Upper knot.	6,400			
30	Nov. 27, "	3.73	4.3	"	" "	7,205			
31	Dec. 10, "	3.90	4.3	"	Lower knot.	6,010			
32	Nov. 25, 1899.	3.53	...	"	Middle knot.	4,555	3,930	40	Ordinary tie in middle; timber hitch at each end.
33	Apr. 5, 1900.	3.53	4.4	"	" "	4,505			
34	Apr. 12, "	3.53	4.4	"	" "	3,915			
35	Nov. 16, "	3.88	4.4	"	" "	3,250			
36	Nov. 17, "	3.75	4.0	"	" "	3,715			
37	Nov 19, "	3.99	4.0	"	" "	3,635			
38	Dec. 11, 1899.	3.53	4.4	"	" "	4,330	4,110	42	Figure 8, bend in middle; timber hitch at each end.
39	Nov. 7, 1900.	3.83	4.3	"	" "	3,135			
40	Nov. 12, "	3.83	4.3	"	" "	3,915			
41	Nov. 12, "	3.79	4.5	"	" "	4,765			
42	Nov. 12, "	3.75	4.4	"	" "	3,745			
43	Nov. 13, "	3.77	4.3	"	" "	4,770	3,260	33	Open hand knot in middle; timber hitch at each end.
44	Dec. 11, 1899.	3.53	4.	"	" "	3,270			
45	Apr. 3, 1900.	3.53	4.4	"	" "	3,165			
46	Apr. 9, "	3.53	4.4	"	" "	3,415			
47	Apr. 10, "	3 53	4 4	"	" "	3,415			
48	Dec. 12, "	3.88	4.0	"	" "	3,030			
49	Dec. 12, "	3.85	4.0	"	" "	3,310	4,380	44	Carrick single in middle; timber hitch at each end.
50	Dec. 12, 1899.	3.53	4 4	"	" "	4,860			
51	Apr. 10, 1900.	3.53	4.4	"	" "	4,055			
52	Oct. 26, "	3.67	4.2	"	" "	4,210			
53	Oct. 29, "	3.68	4.0	"	" "	4,390			

TENSION TESTS ON 3″ MANILA ROPE. (3 strands.)—*Concluded.*

TESTED OVER CAST IRON THIMBLE, 6″ DIAMETER.

Number of test.	Date.	Number of feet per pound.	Number of turns of one strand per foot.	Condition.	Location of break.	Maximum load.	Average strength. (Lbs.)	Efficiency of knot or splice. (Per cent.)	Kind of knot or splice used.
54	Dec. 18, 1899.	3.53	4.0	Dry.	Upper knot.	4,600			
55	Mar. 10, 1900.	3.53	4.5	"	Lower knot.	6,245			
56	Mar. 20, "	3.53	4.4	"	Upper knot.	3,895	4,450	45	Bowline at each end.
57	Mar. 22, "	3.53	4.6	"	Lower knot.	3,805			
58	Mar. 29, "	3.53	4.3	"	Upper knot.	3,645			
59	Oct. 22, "	3 75	4.0	"	" "	4,505			
60	Dec. 18, 1899.	3.53	4.0	"	Lower knot.	3,810			
61	Dec. 20, "	3.53	4.6	"	" "	4,030			
62	Jan. 10, 1900.	3.53	...	"	Upper knot.	3,355	3,670	37	Flemish loop at each end.
63	Oct. 29, "	3 57	4.3	"	" "	3,735			
64	Nov. 13, "	3.80	4.3	"	Lower knot.	3,420			
65	Jan. 1, "	3.53	4.4	"	" "	9,555			
66	Feb. 24, "	3.90	4.4	"	" "	5,955			
67	Mar. 19, "	3.53	4.4	"	Upper knot.	5,755	6,650	67	Clove hitch at each end.
68	Mar. 28, "	3.53	4.4	"	Lower knot.	6,095			
69	Dec. 17, "	4.07	4.0	"	Upper knot.	5,905			
70	Jan. 5, "	3.53	4.4	"	Lower knot.	6,315			
71	Jan. 10, "	3.52	4.4	"	" "	4,655			
72	Mar. 22, "	3.53	4.5	"	Upper knot.	5,490	5,400	55	Timber hitch at each end.
73	Mar. 27, "	3.53	4.5	"	" "	5,325			
74	Mar. 27, "	3.53	4.5	"	" "	5,555			
75	Dec. 17, "	3 90	4.0	"	" "	5,055			
76	Jan. 10, "	3.52	4.4	"	Lower knot.	5,010			
77	Mar. 10, "	3.53	4.5	"	Upper knot.	7,895	5,950	60	Cat's paw at each end.
78	Mar. 27, "	3.53	4 5	"	Lower knot.	5,385			
79	Mar. 29, "	3.53	4.3	"	" "	5,505			

Cement Tests.

PORTLAND CEMENT.—NEAT CEMENT. (Tension.)

Date of test.	Brand.	Per cent. of water used in mixing.	Time of set.	Breaking strength. (Lbs. per sq. in.)
Oct. 31, 1900.	Saylor's.	25	2 days.	526
Oct. 31, "	"	25	2 "	580
Oct. 26, "	"	25	4 "	575
Oct. 26, "	"	25	4 "	620
Nov. 21, "	"	25	5 "	640
Oct. 29, "	"	25	7 "	708
Oct. 29, "	"	25	7 "	708
Oct. 29, "	"	25	7 "	720
Oct. 29, "	"	25	7 "	780
Oct. 29, "	"	25	7 "	740
Nov. 3, "	"	25	7 "	860
Nov. 3, "	"	25	7 "	815
Apr. 2, 1901.	"	25	1 year.	885
Apr. 2, "	"	25	1 "	1,227
Apr. 2, "	"	25	1 "	1,364
Apr. 1, "	"	25	1 "	1,294
Apr. 1, "	"	25	1 "	1,224
Apr. 1, "	"	25	1 "	1,108
Apr. 1, "	"	25	1 "	1,248
Apr. 1, "	"	25	1 "	1,192
Mar. 30, "	"	25	1 "	1,012
Mar. 30, "	"	25	1 "	1,030
Mar. 30, "	"	25	1 "	1,252
Mar. 26, "	"	25	1 "	1,054
Feb. 9, "	"	25	1 "	1,097
Feb. 9, "	"	25	1 "	1,068
Feb. 9, "	"	25	1 "	1,140
Mar. 28, "	"	25	1 "	1,280
Mar. 28, "	"	25	1 "	1,100
Mar. 28, "	"	25	1 "	1,126
Mar. 28, "	"	25	1 "	1,121
Nov. 22, 1900.	Keystone.	25	1 "	1,056
Nov. 22, "	"	25	3 days.	276
Nov. 22, "	"	25	3 "	298
Nov. 22, "	"	25	3 "	322
Nov. 22, "	"	25	3 "	271
Nov. 21, "	"	25	3 "	301
Nov. 21, "	"	25	4 "	332
Nov. 21, "	"	25	4 "	350
Nov. 21, "	"	25	4 "	348
Dec. 15, "	"	25	4 "	320
Dec. 15, "	"	25	5 "	352
Dec. 21, "	"	25	5 "	368
Dec. 21, "	"	25	6 "	386
Dec. 22, "	"	25	6 "	388
Dec. 22, "	"	25	6 "	380
Dec. 22, "	"	25	6 "	383
Dec. 22, "	"	25	6 "	410
Dec. 22, "	"	25	6 "	436
Nov. 27, "	"	25	6 "	445
Nov. 27, "	"	25	7 "	384
Nov. 24, "	"	25	7 "	390
Nov. 24, "	"	25	7 "	424
Dec. 22, "	"	25	7 "	400
Dec. 22, "	"	25	10 "	448
Dec. 22, "	"	25	10 "	424
Dec. 22, "	"	25	10 "	480
Dec. 31, "	"	25	10 "	520
Dec. 31, "	"	25	16 "	545
Dec. 31, "	"	25	17 "	528
Apr. 10, 1901.	"	25	17 "	544
Apr. 10, "	"	25	2 months.	640
		25	2 "	672

PORTLAND CEMENT. — NEAT CEMENT. (Compression.)

Date of test.	Brand.	Per cent. of water used in mixing.	Time of set.	Breaking strength. (2″ cubes.)
Oct. 31, 1900.	Saylor's.	25	2 days.	15,400
Oct. 31, "	"	25	2 "	15,000
Oct. 31, "	"	25	2 "	14,990
Oct. 31, "	"	25	2 "	16,500
Oct. 26, "	"	25	4 "	16,000
Oct. 26, "	"	25	4 "	16,000
Oct. 29, "	"	25	7 "	24,000
Oct. 29, "	"	25	7 "	23,300
Oct. 29, "	"	25	7 "	23,900
Oct. 29, "	"	25	7 "	24,000
Nov. 1, "	"	25	7 "	23,350
Nov. 3, "	"	25	7 "	23,980
Nov. 3, "	"	25	7 "	24,000
Nov. 3, "	"	25	7 "	23,810
Apr. 2, 1901	"	25	1 year.	42,400
Apr. 2, "	"	25	1 "	44,000
Apr. 2, "	"	25	1 "	49,500
Apr. 1, "	"	25	1 "	46,360
Apr. 1, "	"	25	1 "	47,350
Apr. 1, "	"	25	1 "	46,740
Apr. 1, "	"	25	1 "	46,000
Apr. 1, "	"	25	1 "	46,310
Mar. 30, "	"	25	1 "	47,820
Mar. 30, "	"	25	1 "	47,690
Mar. 30, "	"	25	1 "	45,100
Mar. 30, "	"	25	1 "	46,370
Feb. 9, "	"	25	1 "	42,810
Feb. 9, "	"	25	1 "	42,200
Mar. 28, "	"	25	1 "	45,250
Mar. 28, "	"	25	1 "	49,450
Mar. 28, "	"	25	1 "	42,100
Mar. 28, "	"	25	1 "	42,150
Mar. 28, "	"	25	1 "	43,800
Nov. 21, 1900.	Keystone.	25	2 days.	5,650
Nov. 21, "	"	25	2 "	5,490
Nov. 21, "	"	25	2 "	5,630
Dec. 15, "	"	25	5 "	9,970
Dec. 15, "	"	25	5 "	8,100
Nov. 22, "	"	25	7 "	10,850
Nov. 22, "	"	25	7 "	11,850
Nov. 22, "	"	25	7 "	11,050
Nov. 22, "	"	25	7 "	10,050
Jan. 12, 1901.	"	25	7 "	10,000
Jan. 12, "	"	25	7 "	10,700
Jan. 12, "	"	25	7 "	10,440
Jan. 11, "	"	25	9 "	10,000
Jan. 11, "	"	25	9 "	10,100
Jan. 11, "	"	25	9 "	10,050
Jan. 11, "	"	25	9 "	10,630
Dec. 22, 1900.	"	25	9 "	10,900
Dec. 22, "	"	25	10 "	13,200
Dec. 22, "	"	25	10 "	12,750
Dec. 22, "	"	25	10 "	13,320
Dec. 21, "	"	25	11 "	13,280
Dec. 21, "	"	25	11 "	12,580
Dec. 21, "	"	25	11 "	12,850
Dec. 31, "	"	25	16 "	13,600
Dec. 31, "	"	25	16 "	15,540
Apr. 10, 1901.	"	25	2 months.	18,000
Apr. 10, "	"	25	2 "	18,440
Apr. 10, "	"	25	2 "	16,850

PORTLAND CEMENT. — SAND TESTS. (Tension.)

Date of test.	Brand.	Parts sand to one part cement.	Per cent. of water used in mixing.	Time of set.	Breaking strength. (Lbs. per sq. in.)
Nov. 16, 1900.	Saylor's.	3	12	2 days.	97
Nov. 16, "	"	3	12	2 "	155
Nov. 12, "	"	3	12	3 "	96
Nov. 12, "	"	3	12	3 "	106
Nov. 12, "	"	3	12	3 "	122
Nov. 19, "	"	3	12	5 "	188
Nov. 19, "	"	3	12	5 "	183
Nov. 19, "	"	3	12	5 "	177
Nov. 5, "	"	3	12	5 "	145
Nov. 5, "	"	3	12	5 "	167
Nov. 5, "	"	3	12	5 "	157
Mar. 30, 1901.	"	3	12	1 year.	270
Mar. 30, "	"	3	12	1 "	342
Mar. 30, "	"	3	12	1 "	349
Feb. 9, "	"	3	12	1 "	339
Feb. 9, "	"	3	12	1 "	380
Feb. 9, "	"	3	12	1 "	344
Feb. 9, "	"	3	12	1 "	360
Mar. 28, "	"	3	12	1 "	318
Mar. 28, "	"	3	12	1 "	322
Mar. 28, "	"	3	12	1 "	326
Mar. 28, "	"	3	12	1 "	316
Apr. 16, "	Keystone.	3	12	7 days.	73
Apr. 16, "	"	3	12	7 "	89
Apr. 16, "	"	3	12	7 "	90
Nov. 27, 1900.	"	3	12	7 "	76
Nov. 27, "	"	3	12	7 "	81
Nov. 27, "	"	3	12	7 "	86
Nov. 27, "	"	3	12	7 "	89
Jan. 12, 1901.	"	3	12	8 "	94
Jan. 12, "	"	3	12	8 "	90
Jan. 12, "	"	3	12	8 "	84
Apr. 13, "	"	3	12	9 "	93
Apr. 11, "	"	3	12	14 "	118
Apr. 11, "	"	3	12	14 "	118
Apr. 11, "	"	3	12	14 "	98
Jan. 2, "	"	3	12	16 "	115
Apr. 4, "	"	3	12	3 months.	134
Apr. 4. "	"	3	12	3 "	160
Apr. 4, "	"	3	12	3 "	130
Apr. 4, "	"	3	12	3 "	190

PORTLAND CEMENT. — SAND TESTS. (Compression.)

Date of test.	Brand.	Parts sand to one part cement.	Per cent. of water used in mixing.	Time of set.	Breaking strength. (2" cubes.)
Nov. 16, 1900.	Saylor's.	3	12	2 days.	2,000
Nov. 16, "	"	3	12	2 "	2,100
Nov. 16, "	"	3	12	2 "	2,500
Nov. 12, "	"	3	12	2 "	2,000
Nov. 12, "	"	3	12	3 "	2,400
Nov. 12, "	"	3	12	3 "	2,700
Nov. 12, "	"	3	12	3 "	2,200
Nov. 12, "	"	3	12	3 "	2,850
Nov. 12, "	"	3	12	3 "	2,380
Nov. 12, "	"	3	12	3 "	2,200
Nov. 5, "	"	3	12	3 "	2,750
Nov. 5, "	"	3	12	5 "	5,500
Nov. 5, "	"	3	12	5 "	5,670
Nov. 5, "	"	3	12	5 "	6,350
Nov. 5, "	"	3	12	5 "	5,880
Mar. 30, 1901.	"	3	12	5 "	5,810
Mar. 30, "	"	3	12	1 year.	10,000
Mar. 30, "	"	3	12	1 "	12,000
Mar. 28, "	"	3	12	1 "	14,000
Mar. 28, "	"	3	12	1 "	10,800
Mar. 28, "	"	3	12	1 "	15,700
Nov. 27, 1900.	Keystone.	3	12	1 "	12,400
Nov. 27, "	"	3	12	7 days.	2,800
Nov. 27, "	"	3	12	7 "	2,660
Jan. 12, 1901.	"	3	12	7 "	2,835
Jan. 12, "	"	3	12	8 "	2,000
Mar. 28, "	"	3	12	8 "	2,350
Mar. 28, "	"	3	12	14 "	2,410
Mar. 28, "	"	3	12	14 "	2,730
Mar. 28, "	"	3	12	14 "	3,050
Apr. 10, "	"	3	12	14 "	2,480
Apr. 10, "	"	3	12	2 months.	3,200
Apr. 4, "	"	3	12	2 "	2,800
Apr. 4, "	"	3	12	3 "	3,890
Apr. 4, "	"	3	12	3 "	3,650
Apr. 4, "	"	3	12	3 "	3,810
		3	12	3 "	3,250

THE PULSOMETER STEAM PUMP.

By JOSEPH C. RILEY.

THE idea of raising water by condensation of steam and then forcing it to a further elevation by the direct pressure of steam on the surface of the water originated with Captain Thomas Savery, who in 1698 patented his celebrated "fire engine." Properly speaking, the device was not an engine, but a sort of pump, the forerunner of the present pulsometer.

It consisted of two closed vessels, supplied with steam through valves at the top, and provided with pipes through which water could be drawn in and discharged. In operating, one vessel was first filled with steam. The steam valve was then closed, and a spray of cold water injected. The vacuum formed caused water to rise through the suction pipe, filling the vessel. The spray cock was then closed and steam let in, pressing upon the surface of the water and forcing it out through the discharge pipe. By aid of a man to operate the valves, a continuous stream could be maintained from the two vessels.

In those days the demand for pumping machinery came almost entirely from the coal mines, where great need was felt for some form of mechanical pump to take the place of manual labor or animal power. At once Savery's engine found a useful field, but its enormous consumption of steam by useless condensation was everywhere against it, and moreover the very limited height to which it could force water made it quite unfit for use in the deeper collieries. Newcomen's atmospheric engine soon provided mechanical power in a more convenient form, and engineers from that time gave their attention to designing pumps of the piston type. Savery's principle was soon abandoned, and no other successful steam-vacuum pump was produced for nearly two hundred years.

In 1872, Charles H. Hall patented the pulsometer in a form which, though it has since been slightly altered, has remained unchanged in

its essential details. Its principle is simply a modification of Savery's original idea, improved in its application by the use of an automatic steam valve in place of valves requiring a man to operate them. It is no longer limited to small lifts, for much higher steam pressures are now available.

A pulsometer of the old style, made under Hall's patents of 1872 and 1881, is shown in section in Figure 1. It consists of a single casting having two pear-shaped chambers, with tapering necks bent toward each other, and surmounted by another casting in which the two passages unite in a common chamber. At the junction is a brass ball, which oscillates with slight rolling motion, thus closing either of the two chambers to the passage of steam from the supply pipe above. Water is drawn in from below, through the suction valves, one of which is shown in section. It is expelled through the passages *E E*, through the discharge valves, and into the triangular space, shown dotted, and finally is delivered through the vertical pipe. A foot valve in a separate casting below the pump prevents return of the water in the suction pipe. *P P* are the pumping chambers. The circular passage, *S*, is in the front part of the casting, and connects with the air chamber, marked *A*. Two small holes, not shown in the cut, pass from beyond the discharge valves back into the pumping chambers. These are the injection tubes. They are located just below the horizontal upper edges of the discharge passages. Into the three small holes near the top of the chambers, air valves are fitted, their purpose being to admit air to the chambers when the pressure within

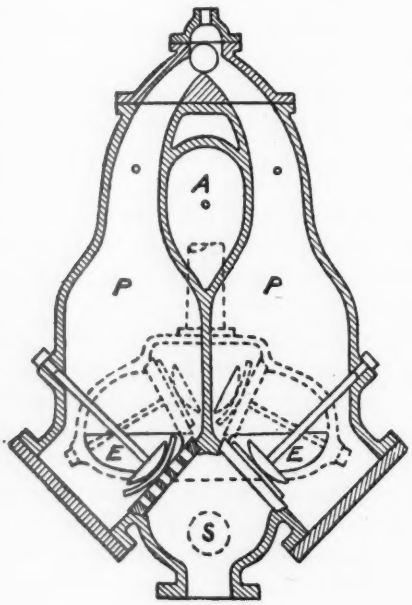

FIG. 1.

is less than that of the atmosphere. The amount which they may open is adjusted by thumb screws.

The operation of the pulsometer is as follows: The ball being at the entrance of the left-hand chamber, and the right-hand being full of water, steam enters, pressing on the surface of the water, and forcing it out through the discharge passage. A rapid condensation of steam occurs from contact with the water and with the walls of the chamber, previously cooled by the water. When the water level has reached the horizontal edge of the discharge passage, a large volume of steam suddenly escapes and is at once condensed by the relatively cold water between the chamber and the discharge valve. The pressure in the chamber quickly decreases; it cannot be sustained by steam from the boiler, for, in accordance with the inventor's first specifications, the steam pipe is small. If now the pressure in the left chamber is equal, or nearly equal, to that in the right, friction caused by the rapid flow of steam past the ball will draw the ball over and close the right-hand chamber. Cut off from further supply, the steam, in contact with water, begins to condense; a jet of cold water from the discharge pipe spurts up through the injection tube, and by breaking into spray against the side of the steam space, completes the condensation. The partial vacuum produced brings water through the suction valve to fill the chamber; but at the same time the air valve admits a little air, which passes up ahead of the water and forms an elastic cushion to prevent the water from striking violently against the steam ball. The air chamber, *A*, is for the purpose of preventing water-hammer in the suction pipe.

In the manner just described, the pump pulsates regularly, steam being condensed, mingling with the water and passing out at the discharge pipe, one chamber pumping while the other is filling, with no external evidence that the pump is working except a slight clicking of the steam valve as it rolls between its seats.

The pulsating action may be further explained by reference to the indicator diagrams of Figure 2. These were taken from a pulsometer like that shown in Figure 1. Crosby indicators with 20-pound springs were used, the cords being pulled simultaneously and uniformly by mechanical means. The indicator pipes entered the three chambers near their highest points. Steam at a gauge pressure of 21 pounds was supplied from a reservoir close at hand. A pressure on the discharge valves of 12.4 pounds was obtained by an actual water column,

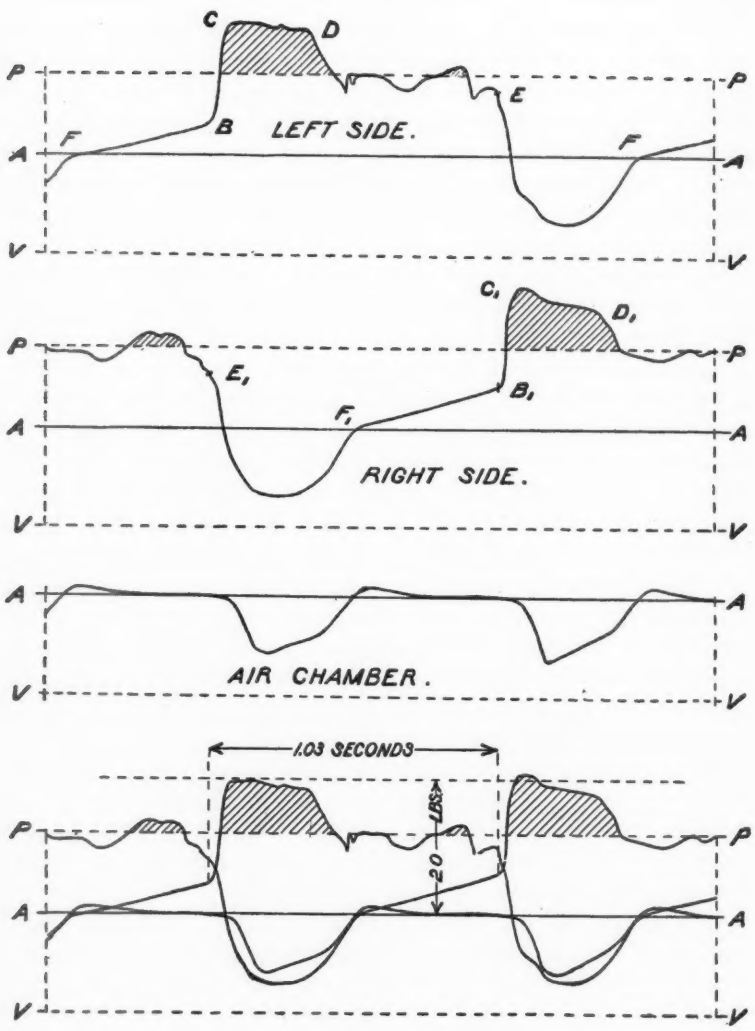

FIG. 2. — INDICATOR DIAGRAMS.

AA, atmospheric line; *PP*, water pressure on discharge valves; *VV*, vacuum line.

not by pumping against a partially closed valve. From the cistern to the suction valves there was a lift of 4 feet; from cistern to steam valve measured 6 feet. The pump was pulsating regularly about once a second, and delivering about 10 cubic feet per minute. The total lift was 33.1 feet.

All of the diagrams are to the same scale. The first three are combined in the fourth. In each diagram, *A A* is the atmospheric line; *V V*, the absolute vacuum line; *P P*, a line showing the water pressure on the discharge valves. In the upper diagram, at *B*, the ball rolls to the right, closing the right side. Steam enters the left chamber, raising the pressure to about 20 pounds at *C*. From *C* to *D*, steam forces the water out of the chamber, but the increase in volume, due to an increasing diameter of the chamber, combined with a more rapid condensation as the water surface spreads out, causes a downward slope of the steam line from *C* to *D*. Meantime, in the right-hand chamber, from E_1 the pressure dropped, by condensation, to below the atmosphere. Water was drawn through the suction valve and air admitted at the air valve until, at F_1 the chamber was nearly filled, or perhaps it is better to say until atmospheric pressure was reached.

Driven by the pressure in the discharge pipe, water continued to be forced back through the right injection tube, compressing the air in the chamber and steadily increasing the pressure from F_1 to B_1. During this time, from *D* to *E*, steam had been escaping from the left-hand chamber into the discharge pipe. The passage of the steam is not uniform, but may be likened to the gulping flow of air into a bottle when filled with water and quickly turned neck downward. This supposition is confirmed by the undulating line drawn by the indicator from below *D* to *E*.

At *E*, the pressure in the left chamber was still a little greater than that in the right at the same instant, but friction of the incoming steam, or the impulse given by it, drew the ball off from its right-hand seat, and closed the left-hand chamber. Thus one pulsation was completed.

It was thought, before taking the diagrams, that the air chamber might play a more important part than proved to be the case. It was found that the air valve of this chamber had to be left open more than either of the other two in order to prevent water-hammer in the suction pipe, for otherwise the supply of air in the chamber was

soon exhausted. This chamber is merely to provide an air cushion for the suction and produce a quiet action of the pump; it is not absolutely necessary — Hall's original pulsometer had none.

Reference to the lowest diagram will show what is happening in all three of the chambers at any instant. The shaded areas, above the discharge pressure line $P\,P$, show when water is being forced through the discharge valves. About one-fourth of the distance across the diagram, from the left, the pressure in the left chamber rose above the discharge pressure. At this moment the pressure in the right chamber fell below the atmosphere. Thus the left pump began to discharge at the instant when the right began to draw its water from the suction pipe. But the left had emptied and steam began to escape before the right was full. This should not be the case. An ideal diagram would show one side discharging while the other is filling, both actions beginning and ending together, and instantly upon their completion the valve should shift and reverse the actions. Delay in moving the valve after the forcing action was completed, produced the great waste of steam between D and E of the upper diagram when steam was blowing through into the discharge pipe, and no pumping at all was done. (The very small shaded area probably represents a redischarge of water which had flowed back into the pumping chamber.) The valve cannot leave its right-hand seat and move toward the left against a great excess of pressure, so that if its motion is to be hastened, the suction period must be shortened and pressure in the chamber which has just filled must increase faster than is shown by the sloping lines $F_1\,B_1$. This might be accomplished by closing the air valve and not allowing any air to enter. The better vacuum thus formed would cause the chamber to fill more quickly, and fill completely with water, and no air being present, the back flow through the injection tube would at once raise the pressure as desired.

But unfortunately such action is impracticable with a steam valve of the ball type. If no air is admitted, the rising water strikes the ball a violent blow and lifts it bodily from its seat, producing very irregular pulsation and sometimes stopping the pumping altogether. Another form of steam valve which is hinged at its top, and swings between its seats, is not subject to this objection, and has been found to give excellent results. Let it be added that the valve of this particular pulsometer was in good condition, and its motion was quite free.

In connection with the time taken to fill a chamber, attention is called to the fact that the indicator, during filling, reached 10 pounds below atmospheric pressure, although the lift was only 4 feet, and the suction pipe was perfectly clear.

The pulsometer from which these diagrams were obtained was tested in January, 1901, at the Massachusetts Institute of Technology. It is known as a No. 4 Pulsometer, of the old style, and was built by the Pulsometer Steam Pump Company, of New York. It has a $\frac{1}{2}$-inch steam pipe, and $2\frac{1}{2}$-inch suction and discharge pipes. The volume of each pumping chamber from steam valve to upper edge of discharge passage is 0.211 cubic feet. Water was fed from a large calibrated tank to a barrel directly underneath the pulsometer, and a constant level maintained in the barrel. The possible error in water measurement was less than 1 per cent.

The discharge pipe was about 3 feet long, having one long sweep bend and leading horizontally into a large tank connected with a 10-inch standpipe. Waste valves on the standpipe made it possible to maintain any desired head with a fluctuation of not more than one-tenth of a foot. Steam was brought from the boiler through an orifice $\frac{5}{16}$ inch in diameter, into a reservoir made of 8-inch pipe, wrapped to prevent condensation. A short piece of $\frac{3}{4}$-inch pipe led from there to the pulsometer, where it was reduced to $\frac{1}{2}$ inch. Especial care was taken to secure perfectly dry steam in the reservoir. Drip cocks on the pipe from the boiler and on the reservoir served to drain what water might collect before starting. Expansion on passing the orifice served to dry, and in some cases to even slightly superheat the steam, as was shown by a thermometer in the reservoir. Dry steam was accordingly assumed in the calculation whenever superheating was not shown.

The quantity of steam used was computed by means of the rise in temperature of the water. Two Centigrade thermometers graduated to tenths of a degree were carefully compared with each other and placed one in the suction and one in the discharge pipe. The readings of one were accepted as read, and those of the other corrected for observed differences in the readings.

The duration of each test was about 20 minutes, but in every case, the pump had been in full operation under constant conditions of lift and steam pressure for at least 10 minutes before beginning the test. The air valves were set to give maximum discharge for each different steam pressure and head on discharge valves. The lift from barrel to

suction valves was 4 feet, and was the same on all the tests. Clear fresh water at a temperature of about 70° was pumped.

Results are given in the following table:

Number of test.	Total lift in feet.	Cubic feet pumped per minute.	Steam in pounds per minute.	Steam pressure by gauge on reservoir.	Excess of steam pressure over water pressure on discharge valves.	Efficiency as a pump.	Pulsations per minute.	Per cent. of full capacity per pulsation.
1	9 6	14.45	3.10	9.9	7.6	.00323	85	80.6
2	9.7	16.84	4 18	15.1	12 7	.00283	100	79.8
3	21 6	8 39	2 68	12 8	5.3	.00486	50	79.6
4	21.5	10 04	2 75	15.3	7 8	.00564	57	83.4
5	21.5	11.53	2 88	17.7	10 2	.00458	62	88 1
6	32 9	10 60	5.18	24 2	11.8	.00479	59	85 3
7	32 9	10 18	4 62	23 0	10 6	.00519	57	84 8
8	46 4	7.10	4.37	23 1	5.0	.00543	48	70.1
9	46 6	9.37	4 70	28 9	10 7	.00669	53	83.7
10	46.7	10.70	5.71	34.0	15.7	.00632	56	90.6
11	60.0	8 42	4.65	32 4	8 3	.00775	49	81 4
12	60.1	9 14	5 21	34 0	9 8	.00755	52	83 3
13	60 2	10 14	5 45	37.5	13 3	.00802	53	90 7
14	72 5	8 52	5.11	38.0	8 5	.00850	53	76.3
15	72 6	9 19	6.03	42.7	13.1	.00779	54	80 6
16	72 6	9 33	6 12	42 8	13 2	.00784	54	81.8
17	72 6	10.02	6.81	46.8	17.3	.00760	54	88.1

It appears that for each discharge head there is a certain most effective steam pressure, which in general is from 8 to 13 pounds higher than the water pressure on the discharge valves. If this is exceeded, irregular pulsation will occur, and if greatly exceeded, steam will blow continuously into the discharge pipe, and the pump will fail to operate. The effect of too slight an excess of steam pressure and

consequent slow pulsation is indicated in the low efficiency of Test 8, caused partly by long contact of the steam with the water, and partly by return of an excessive quantity of water through the injection tubes during the suction periods.

The efficiency shown in these tests is lower than those about to be mentioned; but it must be remembered that the pump is a small one, and that the cards show an imperfect application of the designer's principle, though perhaps as good a one as can be obtained from this pump.

Hartmann and Knoke give results of tests made at Bromberg in 1886, on a pulsometer of Haussmann's patent. This pulsometer had for a steam valve a metal piston moved horizontally from side to side by the difference of steam pressure upon its ends which were connected by small passages to the lower part of the pumping chambers. The size of the pump is not stated.

The results obtained are given in the following table:

Number of test.	Suction in feet.	Total lift.	Cubic feet pumped per minute.	Steam in pounds per minute.	Steam pressure by gauge.	Efficiency as a pump.	Pulsations per minute.	Rise in temperature of water, degrees Fahrenheit.	B. T. U. per minute given up by steam.	B. T. U. necessary to heat water and to pump.
1	4.3	51.2	7.86	3 24	42.6	.00877	26	4 66	3,670	2,300
2	5.7	51.5	8 18	3 41	44 1	.00871	26	2 34	3,860	1,220
3	7.0	51.3	5.41	2 42	44.1	.00807	21	2.16	2,740	750
4	9.0	51.7	7.55	3.60	42.6	.00767	25	4.32	4,070	2,060
5	9.2	51.1	6 41	2 73	44.1	.00845	23	.52	3,090	233
6	10 6	51 6	8.39	4.36	41.2	.00701	30	.63	4,940	364
7	12 6	50.3	10.42	4.53	41.2	.00819	42	3.60	5,130	2,380
8	14.2	51.3	6.56	2 83	44.1	.00833	25	1.26	3,210	540
9	14 4	50.5	11.09	4.97	36 8	.00454	44	2.70	5,620	1,900
10	17.0	49.8	5.64	2 37	42.6	.00837	27	2.70	2,680	970
11	18 7	51 5	6.84	2 57	44.1	.00966	28	2.12	2,910	930

The intention in these tests seems to have been to vary the suction lift and the discharge lift without changing their sum, and

so determine the most advantageous height at which to place the pulsometer in order to secure most efficient action. This is an important question, but it cannot be answered from the results of these tests. In the absence of more complete information concerning the accuracy with which the measurements were made, it is impossible to say what reliance can be placed upon the results. It is certain, however, that the heat accounts do not balance well. They were computed on the assumption that dry steam was supplied, and that the final temperature was 70° F. In these tests, the steam used was measured at the boiler, a method which is inexact at its best.

Tests on a pulsometer with 4-inch suction and delivery pipes were made by students of Stevens Institute, under the direction of Professor Wood, in 1891, and reported to the American Society of Mechanical Engineers. The steam used was calculated from the increase in temperature of the water. The water pumped was measured by a meter. A summary of the tests is given in the following table:

Number of test.	Suction lift in feet.	Discharge lift in feet.	Cubic feet pumped per minute.	Steam in pounds per minute.	Pressure of steam by gauge.	Probable excess of steam pressure over water pressure on discharge valves.	Pulsations per minute.	Efficiency as a pump.
1	12 3	30	36.1	8.98	19	6.0	71	.0120
2	12.3	54	16.6	5.18	30	6 6	60	.0155
3	19.7	54	20.4	8 44	44	20 4	57	.0126
4	19.7	30	22.1	5.67	26	13.1	64	.0138

Of the first two tests with equal suction lifts, the one having the higher discharge lift showed the greater efficiency. Of Tests 1 and 4, with equal discharge lifts, the one having the higher suction lift showed the greater efficiency. Tests 3 and 4 were made with equal suction lifts, but in 3 the discharge lift was higher than in 4, and yet 4 showed the greater efficiency. This was probably due to too large an excess of steam pressure in Test 3.

At an industrial exposition held at Görlitz in 1885, a very large pulsometer was used to supply water for an artificial cascade. This pulsometer, built by a firm of German engineers, was after Hall's pat-

tern, but had an improved form of steam valve, consisting of a tongue of metal suspended at the top and free to oscillate through the small space between the valve seats. This form of valve was mentioned in the discussion of valve action as shown by the diagrams.

The pumping chambers measured 23 inches in diameter at their lower ends, and had each a volume of 3.95 cubic feet, measured from the steam valve to the discharge passage. The discharge pipe was 111 feet long, $8\frac{7}{8}$ inches in diameter, and had several elbows. Two tests made by Eichler gave the following results:

	1	2
Total lift in feet	29.5	29.5
Suction lift in feet	3 3	3.3
Cubic feet pumped per minute	141.3	141.0
Steam used, pounds per minute	11 0	13 8
Steam pressure, pounds per square inch above atmosphere	23 5	26 5
Probable excess of steam pressure over water pressure on discharge valves	13 6	16 6
Pulsations per minute	40	42
Per cent. of full capacity per pulsation	90	85
Foot pounds work done per pound steam	23,700	18,800
Efficiency — assuming dry steam and a discharge temperature of 70°,	.0271	.0215

These performances are considered to be particularly economical ones, and are doubtless due in part to the immense size of the pulsometer, although Eichler ascribed most of the gain in efficiency to the favorable action of his pendulum steam valve. In these tests the lifts were constant. No greater discharge resulted in Test 2 than in Test 1, although steam of higher pressure was used. It is thought that the pressure was too high. Attention is called to the excess of steam pressure over water pressure. Hartmann and Knoke state that this excess should be at least half an atmosphere, and better still, three-quarters or a whole atmosphere. This may be compared with the results obtained at the Massachusetts Institute of Technology.

Mention, at least, should be made of the Grel valve, an arrangement sometimes placed in the neck of a pulsometer above the steam

ball. Its action is analogous to that of an independent cut-off valve on a steam engine; it shuts off the steam before the pumping stroke is completed, allowing the steam to do work by expansion during the remainder of the stroke. This valve is said to effect a saving of over 25 per cent. in the steam consumption.

Regarding the relative efficiency of pulsometers when compared with piston steam pumps, in spite of what the makers claim, actual tests show a very wasteful record for the pulsometers. Eichler's large pulsometer at Görlitz gave the remarkably high efficiency of 2.7 per cent., but a good duplex pump of the same capacity, about 1,000 gallons per minute, may easily return a duty of 28,000,000 foot-pounds per 1,000,000 thermal units, which means an efficiency of 3.6 per cent. The economy of smaller pulsometers is very much less, though of course, they must be compared with the class of piston pumps generally used for handling small quantities, that is, with direct acting piston pumps which operate their own valves, not with duplex pumps.

But notwithstanding its wasteful use of steam, the pulsometer is well qualified to compete with other pumps for some kinds of work. Its entire lack of moving parts or rubbing surfaces is a great advantage where it must stand rough usage, or where the liquid to be pumped contains grit or sand. Equipped with a simpler form of valve in place of the rubber discs, it will successfully pump very thick liquids or semi-fluids, such as heavy syrups, or even liquid mud. It is often used in chemical works and tanneries for pumping corrosive liquids. For temporary work in draining excavations, or in emergencies, such as wrecking operations where a powerful pump must be put at work in the shortest possible time, the pulsometer is peculiarly adapted, since it requires no foundation whatever, but can be slung from a chain and supplied with steam through a flexible hose.

BOSTON, 1901.

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